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PATENT TRADEMARK OFFICE

CHAPTER II

**TRANSMITTAL LETTER
TO THE UNITED STATES ELECTED OFFICE (EO/US)**

(ENTRY INTO U.S. NATIONAL PHASE UNDER CHAPTER II)

PCT/IL00/00201	30 MARCH 2000	30 MARCH 1999
INTERNATIONAL APPLICATION NO.	INTERNATIONAL FILING DATE	PRIORITY DATE CLAIMED

A METHOD AND SYSTEM FOR SUPER RESOLUTION

TITLE OF INVENTION

David MENDLOVIC and Zeev ZALEVSKY

APPLICANT(S)

Box PCT
Assistant Commissioner for Patents
Washington D.C. 20231
ATTENTION: EO/US

NOTE: The completion of those filing requirements that can be made at a time later than 30 months from the priority date results from the Commissioner exercising his judgment under the authority granted under 35 USC 371(d). The filing

CERTIFICATION UNDER 37 C.F.R. 1.10*

*(Express Mail label number is **mandatory**.)*

(Express Mail certification is optional.)

I hereby certify that this correspondence and the documents referred to as attached therein are being deposited with the United States Postal Service on this date SEPTEMBER 27, 2001, in an envelope as "Express Mail Post Office to Addressee," Mailing Label Number EL728245245US, addressed to the: Assistant Commissioner for Patents, Washington, D.C. 20231.

BARBARA D. SANTIAGO

(type or print name of person mailing paper)

Barbara D. Santiago
Signature of person mailing paper

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receipt will show the actual date of receipt of the last item completing the entry into the national phase. See 37 C.F.R. §1.491 which states: "An international application enters the national state when the applicant has filed the documents and fees required by 35 USC 371(c) within the periods set forth in § 1.494 and § 1.495."

WARNING: Where the items are those which can be submitted to complete the entry of the international application into the national phase are subsequent to 30 months from the priority date the application is still considered to be in the international state and if mailing procedures are utilized to obtain a date the express mail procedure of 37 C.F.R. §1.10 must be used (since international application papers are not covered by an ordinary certificate of mailing - See 37 C.F.R. §1.8.

NOTE: Documents and fees must be clearly identified as a submission to enter the national state under 35 USC 371 otherwise the submission will be considered as being made under 35 USC 111. 37 C.F.R. § 1.494(f).

1. Applicant herewith submits to the United States Elected Office (EO/US) the following items under 35 U.S.C. 371:
 - a. ☒ This express request to immediately begin national examination procedures (35 U.S.C. 371(f)).
 - b. ☒ The U.S. National Fee (35 U.S.C. 371(c)(1)) and other fees (37 C.F.R. § 1.492) as indicated below:

2.Fees

CLAIMS FEE	(1) FOR	(2) NUMBER FILED	(3) NUMBER EXTRA	(4) RATE	(5) CALCULATIONS
<input type="checkbox"/> *	TOTAL CLAIMS	64- 20 =	44	x \$ 18.00 =	\$NOT PAID
	INDEPENDENT CLAIMS	4- 3 =	1	x \$ 80.00 =	NOT PAID
	MULTIPLE DEPENDENT CLAIM(S) (if applicable) + \$270.00				
BASIC FEE**	<input type="checkbox"/> U.S. PTO WAS INTERNATIONAL PRELIMINARY EXAMINATION AUTHORITY Where an International preliminary examination fee as set forth in § 1.482 has been paid on the international application to the U.S. PTO: <input type="checkbox"/> and the international preliminary examination report states that the criteria of novelty, inventive step (non-obviousness) and industrial activity, as defined in PCT Article 33(2) to (4) have been satisfied for all the claims presented in the application entering the national stage (37 CFR 1.492(a)(4)) \$100.00 <input type="checkbox"/> and the above requirements are not met (37 CFR 1.492(a)(1)) \$690.00				
	<input checked="" type="checkbox"/> U.S. PTO WAS NOT INTERNATIONAL PRELIMINARY EXAMINATION AUTHORITY Where no international preliminary examination fee as set forth in § 1.482 has been paid to the U.S. PTO, and payment of an international search fee as set forth in § 1.445(a)(2) to the U.S. PTO: <input type="checkbox"/> has been paid (37 CFR 1.492(a)(2)) \$710.00 <input type="checkbox"/> has not been paid (37 CFR 1.492(a)(3)) \$1,000.00 <input checked="" type="checkbox"/> where a search report on the international application has been prepared by the European Patent Office or the Japanese Patent Office (37 CFR 1.492(a)(5)) \$860.00				
	Total of above Calculations				=\$860.00
SMALL ENTITY	Reduction by ½ for filing by small entity, if applicable. Statement may also be filed. (note 37 CFR 1.9, 1.27, 1.28)				-
	Subtotal				\$860.00
	Total National Fee				\$860.00
	Fee for recording the enclosed assignment document \$40.00 (37 CFR 1.21(h)). (See Item 13 below). See attached "ASSIGNMENT COVER SHEET".				
TOTAL	Total Fees enclosed				\$860.00

*See attached Preliminary Amendment Reducing the Number of Claims.

- i. ☒ A check in the amount of \$860.00 to cover the above fees is enclosed.
 ii. ☐ Please charge Account No. _____ in the amount of \$ _____.
 A duplicate copy of this sheet is enclosed.

****WARNING:** "To avoid abandonment of the application the applicant shall furnish to the United States Patent and Trademark Office not later than the expiration of 30 months from the priority date: * * * (2) the basic national fee (see § 1.492(a)). The 30-month time limit may not be extended." 37 C.F.R. § 1.495(b).

WARNING: If the translation of the international application and/or the oath or declaration have not been submitted by the applicant within thirty (30) months from the priority date, such requirements may be met within a time period set by the Office 37 C.F.R. § 1.495(b)(2). The payment of the surcharge set forth in § 1.492(e) is required as a condition for accepting the oath or declaration later than thirty (30) months after the priority date. The payment of the processing fee set forth in § 1.492(f) is required for acceptance of an English translation later than thirty (30) months after the priority date. Failure to comply with these requirements will result in abandonment of the application. The provisions of § 1.136 apply to the period which is set. Notice of Jan. 3, 1993, 1147 O.G. 29 to 40.

3. ☒ A copy of the International application as filed (35 U.S.C. 371(c)(2)):

NOTE: Section 1.495 (b) was amended to require that the basic national fee and a copy of the international application must be filed with the Office by 30 months from the priority date to avoid abandonment "The International Bureau normally provides the copy of the international application to the Office in accordance with PCT Article 20. At the same time, the International Bureau notifies applicant of the communication to the Office. In accordance with PCT Rule 47.1, that notice shall be accepted by all designated offices as conclusive evidence that the communication has duly taken place. Thus, if the applicant desires to enter the national stage, the applicant normally need only check to be sure the notice from the International Bureau has been received and then pay the basic national fee by 30 months from the priority date " Notice of Jan. 7, 1993, 1147 O.G. 29 to 40, at 35-36. See item 14c below.

- a. ☐ is transmitted herewith.
 b. ☐ is not required, as the application was filed with the United States Receiving Office.
 c. ☒ has been transmitted
 i. ☒ by the International Bureau.
 Date of mailing of the application (from form PCT/IB/308): _____.
 ii. ☐ by applicant on _____
 Date

4. ☒ A translation of the International application into the English language (35 U.S.C. 371(c)(2)):
 a. ☐ is transmitted herewith.
 b. ☒ is not required as the application was filed in English.
 c. ☐ was previously transmitted by applicant on _____
 Date
 d. ☐ will follow.

5. ☒ Amendments to the claims of the International application under PCT Article 19 (35 U.S.C. 371(c)(3)):

NOTE: The Notice of January 7, 1993 points out that 37 C.F.R. § 1.495(a) was amended to clarify the existing and continuing practice that PCT Article 19 amendments must be submitted by 30 months from the priority date and this deadline may not be extended. The Notice further advises that: "The failure to do so will not result in loss of the subject matter of the PCT Article 19 amendments. Applicant may submit that subject matter in a preliminary amendment filed under section 1.121. In many cases, filing an amendment under section 1.121 is preferable since grammatical or idiomatic errors may be corrected." 1147 O.G. 29-40, at 36.

- a. ☐ are transmitted herewith.
 - b. ☐ have been transmitted
 - i. ☐ by the International Bureau.
Date of mailing of the amendment (from form PCT/IB/308): _____.
 - ii. ☐ by applicant on _____.
Date
 - c. ☒ have not been transmitted as
 - i. ☒ applicant chose not to make amendments under PCT Article 19.
Date of mailing of Search Report (from form PCT/ISA/210): 24 JULY 2000.
 - ii. ☐ the time limit for the submission of amendments has not yet expired.
The amendments or a statement that amendments have not been made will be transmitted before the expiration of the time limit under PCT Rule 46.1.
6. ☒ A translation of the amendments to the claims under PCT Article 19 (38 U.S.C. 371(c)(3)):
- a. ☐ is transmitted herewith.
 - b. ☐ is not required as the amendments were made in the English language.
 - c. ☒ has not been transmitted for reasons indicated at point 5(c) above.
7. ☒ A copy of the international examination report (PCT/IPEA/409)
- ☒ is transmitted herewith.
 - ☐ is not required as the application was filed with the United States Receiving Office.
8. ☐ Annex(es) to the international preliminary examination report
- a. ☐ is/are transmitted herewith.
 - b. ☐ is/are not required as the application was filed with the United States Receiving Office.
9. ☐ A translation of the annexes to the international preliminary examination report
- a. ☐ is transmitted herewith.
 - b. ☐ is not required as the annexes are in the English language.

10. ☒ An oath or declaration of the inventor (35 U.S.C. 371(c)(4)) complying with 35 U.S.C. 115
- a. ☐ was previously submitted by applicant on _____.
Date
- b. ☐ is submitted herewith, and such oath or declaration
- i. ☐ is attached to the application.
- ii. ☐ identifies the application and any amendments under PCT Article 19 that were transmitted as stated in points 3(b) or 3(c) and 5(b); and states that they were reviewed by the inventor as required by 37 C.F.R. 1.70.
- c. ☒ will follow.

Other document(s) or information included:

11. ☒ An International Search Report (PCT/ISA/210) or Declaration under PCT Article 17(2)(a):
- a. ☒ is transmitted herewith.
- b. ☐ has been transmitted by the International Bureau.
Date of mailing (from form PCT/IB/308): _____.
- c. ☐ is not required, as the application was searched by the United States International Searching Authority.
- d. ☐ will be transmitted promptly upon request.
- e. ☐ has been submitted by applicant on _____.
Date
12. ☒ An Information Disclosure Statement under 37 C.F.R. 1.97 and 1.98:
- a. ☐ is transmitted herewith.
Also transmitted herewith is/are:
- ☐ Form PTO-1449 (PTO/SB/08A and 08B).
- ☐ Copies of citations listed.
- b. ☒ will be transmitted within THREE MONTHS of the date of submission of requirements under 35 U.S.C. 371(c).
- c. ☐ was previously submitted by applicant on _____.
Date
13. ☐ An assignment document is transmitted herewith for recording.

A separate ☐ "COVER SHEET FOR ASSIGNMENT (DOCUMENT) ACCOMPANYING NEW PATENT APPLICATION" or ☐ FORM PTO 1595 is also attached.

14. ☒ Additional documents:
- a. ☐ Copy of request (PCT/RO/101)
 - b. ☒ International Publication No. WO 00/59206
 - i. ☒ Specification, claims and drawing
 - ii. ☐ Front page only
 - c. ☐ Preliminary amendment (37 C.F.R. § 1.121)
 - d. ☐ Other
- _____
- _____
- _____
15. ☒ The above checked items are being transmitted
- a. ☒ before 30 months from any claimed priority date.
 - b. ☐ after 30 months.
16. ☐ Certain requirements under 35 U.S.C. 371 were previously submitted by the applicant on _____, namely:
- _____
- _____
- _____

AUTHORIZATION TO CHARGE ADDITIONAL FEES

WARNING: *Accurately count claims, especially multiple dependent claims, to avoid unexpected high charges if extra claims are authorized.*

NOTE: *"A written request may be submitted in an application that is an authorization to treat any concurrent or future reply, requiring a petition for an extension of time under this paragraph for its timely submission, as incorporating a petition for extension of time for the appropriate length of time. An authorization to charge all required fees, fees under § 1.17, or all required extension of time fees will be treated as a constructive petition for an extension of time in any concurrent or future reply requiring a petition for an extension of time under this paragraph for its timely submission. Submission of the fee set forth in § 1.17(a) will also be treated as a constructive petition for an extension of time in any concurrent reply requiring a petition for an extension of time under this paragraph for its timely submission." 37 C.F.R. § 1.136(a)(3).*

NOTE: *"Amounts of twenty-five dollars or less will not be returned unless specifically requested within a reasonable time, nor will the payer be notified of such amounts; amounts over twenty-five dollars may be returned by check or, if requested, by credit to a deposit account." 37 C.F.R. § 1.26(a).*

☒ The Commissioner is hereby authorized to charge the following additional fees that may be required by this paper and during the entire pendency of this application to Account No. 12-0425.

☒ 37 C.F.R. 1.492(a)(1), (2), (3), and (4) (filing fees)

WARNING: *Because failure to pay the national fee within 30 months without extension (37 C.F.R. § 1.495(b)(2)) results in abandonment of the application, it would be best to always check the above box.*

☐ 37 C.F.R. 1.492(b), (c) and (d) (presentation of extra claims)

NOTE: *Because additional fees for excess or multiple dependent claims not paid on filing or on later presentation must*

only be paid or these claims cancelled by amendment prior to the expiration of the time period set for response by the PTO in any notice of fee deficiency (37 C.F.R. § 1.492(d)), it might be best not to authorize the PTO to charge additional claim fees, except possible when dealing with amendments after final action.

- ☒ 37 C.F.R. 1.17 (application processing fees)
- ☒ 37 C.F.R. 1.17(a)(1)-(5)(extension fees pursuant to § 1.136(a).
- ☒ 37 C.F.R. 1.18 (issue fee at or before mailing of Notice of Allowance, pursuant to 37 C.F.R. 1.311(b))

NOTE: Where an authorization to charge the issue fee to a deposit account has been filed before the mailing of a Notice of Allowance, the issue fee will be automatically charged to the deposit account at the time of mailing the notice of allowance. 37 C.F.R. § 1.311(b).

NOTE: 37 C.F.R. 1.28(b) requires "Notification of any change in loss of entitlement to small entity status must be filed in the application . . . prior to paying, or at the time of paying . . . issue fee." From the wording of 37 C.F.R. § 1.28(b): (a) notification of change of status must be made even if the fee is paid as "other than a small entity" and (b) no notification is required if the change is to another small entity.

- ☐ 37 C.F.R. § 1.492(e) and (f) (surcharge fees for filing the declaration and/or filing an English translation of an International Application later than 30 months after the priority date).

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13/pst
A Method and System for Super Resolution

FIELD OF THE INVENTION

The present invention relates to super resolution enhancement of sampled data.

BACKGROUND OF THE INVENTION

Super-resolution refers to the enhancement of resolutions for images of scenery or objects acquired by an image capture device, such as a scanner or a CCD video camera, beyond the resolution inherent in the capture device, and beyond other limitations of the capture device. Super-resolution is used primarily to enhance the quality of captured images, and to increase the information content therein.

Many super-resolution techniques used with imaging sensors are based on micro scanning operations. When using micro-scanning operations, a scene or object being captured is sampled multiple times, each time with a sub pixel shift applied.

Prior art techniques for super-resolution do not achieve exact super resolution, but rather they perform over-sampling. Exact super resolution is limited by the fill factor; i.e., the ratio between the area of the region sensitive to radiation and the pitch. The pitch is the area between centers of adjacent detectors in a sensor panel – equivalently, the pitch is the area between adjacent pixels. For example, if the sensitivity to radiation only extends over half the distance separating detectors, then the fill factor is $0.5 * 0.5 = 25\%$. With a 25% fill factor, exact super-resolution using prior art methods can be obtained up to a factor of two in resolution in each dimension, since the regions of sensitivity to radiation are only half the size of the pitch, and can thus be shifted by half-pixels in each dimension without overlapping. Additional super-resolution, beyond a factor of two, has been achieved by prior art methods at the expense of decreased contrast.

For a fill factor of 80%, which is typical for image sensing devices, the limitation on exact super-resolution is $\frac{1}{\sqrt{0.8}} \approx 1.12$. The experimental barrier is approximately at a factor of 1.5, with some decrease in contrast.

Prior art methods for obtaining super resolution from captured images are based on estimating signal distortion. These methods perform optimal estimation of signal distortion from the captured images, using Bayesian techniques and using criteria such as Maximum Entropy. These methods are advantageous when image acquisition is made over a large distance (such as satellite data acquired from outer space), since atmospheric transmission and turbulence have a major impact on limiting the resolution obtained.

One such method is described in I. Cheeseman, B. Kanefsky, R. Kraft, J. Stutz, R. Hanson, "Super-Resolved Surface Reconstruction from Multiple Images," in Maximum Entropy and Bayesian Methods, G. R. Heidbreder (ed.), Kluwer, the Netherlands, 1996, pgs. 293 - 308. This method is based on inverse graphics theory, and is used for ground modeling from outer space observations. An initial ground model is formed by letting each pixel "vote" on what the corresponding ground position should be, based upon the extent that the corresponding ground position contributes to that pixel. The initial ground model is then used to project what an image should be (i.e., predict each pixel value). The differences between the predicted pixel values and the observed pixel values are used to update the ground model until it cannot be further improved. This procedure produces an increase in both spatial resolution and gray-scale resolution.

Another such method is described in A. Zomet and S. Peleg, "Applying Super-Resolution to Panoramic Mosaics," IEEE Workshop on Applications of Computer Vision, Princeton, Oct 1998. This method attains super resolution using an iterative method for mosaicing. Given a video sequence scanning a static scene, a panoramic image can be constructed whose field of view is the entire scene. Each region in the panorama is covered by many overlapping image segments, and this can be exploited to enhance its resolution.

Another such method is described in Pearson, T. J. and Readhead, A. C. S. "Image Formation by Self-Calibration in Radio Astronomy," Ann. Rev. Astron. Astrophys. 22, 1984, pgs. 97-130. This method uses non linear methods, and is based on optimal spectrum estimation.

SUMMARY OF THE INVENTION

The present specification concerns data obtained by sampling a continuous signal, and describes methods and systems for enhancing the resolution of the data. For example, a barcode reader samples a barcode when scanning it, and the present invention can be used to enhance the resolution of the sampled data, thereby providing a better reconstruction of the barcode. For another example, a CCD camera samples an object or scene being viewed, to produce a digital image, and the present invention can be used to enhance the resolution of the digital image, thereby providing a better quality image.

The present invention enhances sampled data by effectively decreasing the sampling period. When used with digital images, the present invention provides sub-pixel accuracy. An original image quantized into pixel area elements can be enhanced using the present invention to a finer granularity quantization with sub-pixel area elements. For example, the enhanced image can have one-eighth pixel granularity.

The present invention overcomes the limitation of prior art methods to achieve exact resolution improvement by more than a factor of 1.5. Using the present invention, any desired resolution improvement may be obtained by attaching an appropriately designed mask to a sensor plane of a capture device.

There is provided in accordance with a preferred embodiment of the present invention a method for enhancing the resolution of an image sensing device, including the steps of attaching a mask to a panel of detectors in an image sensing device, generating multiple fields of view, the multiple fields of view being related to one another by sub-pixel shifts, acquiring multiple images with the image sensing device from the multiple fields of view, and combining the multiple images into an enhanced image of higher pixel resolution than the pixel resolutions of the multiple images.

There is further provided in accordance with a preferred embodiment of the present invention a system for enhancing the resolution of an image sensing device, including an image sensing device comprising a panel of detectors, a mask attached to said panel of detectors, a motion generator generating multiple fields of view, the multiple fields of view being related to one another by sub-pixel shifts, image acquisition circuitry housed within said image sensing device acquiring multiple images from the multiple fields of view, and a combiner combining the multiple images into an enhanced image of higher pixel resolution than the pixel resolutions of the multiple images.

There is still further provided in accordance with a preferred embodiment of the present invention a method for enhancing the resolution of an image sensing device, including the steps of creating replicas of fields of view using an optical element attached to an image sensing device, acquiring multiple images with the sensing device from the replicas of fields of view, and combining the multiple images into an enhanced image of higher pixel resolution than the pixel resolutions of the multiple images.

There is additionally provided in accordance with a preferred embodiment of the present invention a system for enhancing the resolution of an image sensing device, including an image sensing device, an optical element attached to the image sensing device, the optical element being such as to create replicas of fields of view, image acquisition circuitry housed within the image sensing device acquiring multiple images from the replicas of fields of view, and a combiner combining the multiple images into an enhanced image of higher pixel resolution than the pixel resolutions of the multiple images.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be more fully understood and appreciated from the following detailed description, taken in conjunction with the drawings in which:

Figure 1 is an illustration of a one-dimensional cross-section of a prior art image sensing device, such as a CCD camera or a scanner;

Figure 2 is a prior art illustration of a pixel sensitivity (apodization) function, for modeling averaged light intensity arriving at a detector;

Figures 3A - 3C are illustrations of the results of computer simulations of a preferred embodiment of the present invention, as applied to CCD cameras;

Figures 4A - 4D are further illustrations of the results of computer simulations of a preferred embodiment of the present invention, as applied to CCD cameras;

Figures 5A - 5C are illustrations of the results of computer simulations of a preferred embodiment of the present invention, as applied to barcode readers;

Figure 6 is an illustration of three samplings of an object by a sensing device, separated by sub-pixel shifts, in accordance with a preferred embodiment of the present invention;

Figure 7 is a simplified illustration of a mask attached to a sensor panel of array detectors in an image sensing device, in accordance with a preferred embodiment of the present invention;

Figure 8 illustrates the shape of a mask in accordance with a preferred embodiment of the present invention;

Figures 9A - 9J illustrate the use of a mask in obtaining super-resolution, in accordance with a preferred embodiment of the present invention;

Figure 10 illustrates an enhanced image obtained by applying super-resolution to the low resolution CCD captured image illustrated in Figure 3B, without the use of a mask; and

Figure 11 is a simplified illustration of an alternating ("checkerboard") mask attached to a sensor panel of array detectors in an image sensing device, in accordance with a preferred embodiment of the present invention.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

The present invention concerns digital images captured by digital image acquisition devices, such as digital cameras and scanners, and provides a method and system for obtaining super-resolution imagery. Super-resolution refers to the ability to obtain a resolution of a digital image that is greater than that native resolution of the image acquisition device. The present invention uses multiple low resolution captures of a picture to obtain a high resolution digital image. For example, if 64 images of an object are captured by a CCD camera having a spatial resolution of 32×32 pixels, the present invention can be used to integrate the captured data and provide a digital image of the object at a spatial resolution of 256×256 pixels. The present invention makes efficient use of captured image data, in that there is a direct one-to-one relationship between the number of images captured and the ratio of resolution enhancement. That is, if K images are captured then the present invention enhances resolution of the capture device by a factor of K .

Additionally, the present invention applies to acquisition devices, regardless of their dynamic color range. In the example described above, the CCD camera can have as low as 1 bit per pixel color depth, or as high as 8 bits per pixel and higher, and the present invention is applicable.

As used in the present specification in reference to digital images, the terms "low resolution" and "high resolution" are intended to be relative terms, used to indicate an advantage of the present invention in providing digital images of an input object at a higher resolution than those produced by an image acquisition device.

Reference is now made to Figure 1, which illustrates a one-dimensional cross-section of a prior art image sensing device, such as a CCD camera or a scanner. An image sensing device 100 consists of an array of detectors 110 in a sensing panel (not shown), each of which measures a light intensity of a scene 120 at a specific pixel location. Light rays 130 emanating from scene 120 are diffracted by a lens 140, and arrive at detectors 110.

The array of detectors 110 in the sensing panel is two-dimensional, and the one-dimensional array of detectors illustrated in Figure 1 is but a single cross-section of the two-dimensional array. Similarly, Figure 1 illustrates a single cross-section of scene 120. The direction of the one-dimensional array of detectors is denoted by a variable x , and the light intensity of the scene is correspondingly denoted by $u(x)$. The variable x is a continuous

variable, and scene 120 corresponds to a continuous signal. The array of detectors 110 samples scene 120, and produces a discrete digital image, comprising pixel locations and pixel color intensities. The spacings between detectors corresponds to the pixel size for the sampled digital image, and is referred to as the "pitch."

Reference is now made to Figure 2, which illustrates a one-dimensional cross-section of a prior art pixel sensitivity (apodization) function, for modeling averaged light intensity arriving at a detector. The measured light intensity at each detector 110 (Figure 1) is not a measure of the light intensity at a single point location of scene 120. Instead, it is an average intensity, averaged by a pixel sensitivity function $g(x)$, or apodization. The pixel sensitivity function is illustrated as a one-dimensional function $g(x)$ in Figure 2, but $g(x)$ is only a single cross-section of a two-dimensional pixel sensitivity function $g(x, y)$.

The support of the two-dimensional pixel sensitivity function corresponds to the region that is sensitive to radiation. This region typically extends across an area that is contained within the area between neighboring pixel centers. The ratio between the area of the two-dimensional support of the pixel sensitivity function and the area between pixel centers containing it is referred to as the "fill factor."

It is the averaging with $g(x)$ that gives rise to complications in obtaining exact super-resolution in prior art methods.

Reference is now made to Figures 3A - 3C, which illustrate the results of computer simulations of a preferred embodiment of the present invention, as applied to CCD cameras. Figure 3A shows an input picture with spatial resolution of 256 x 256 pixels. Figure 3B shows an image of the input picture, captured by a CCD camera having a spatial resolution of 32 x 32 pixels, and 8 bits per pixel color depth. Figure 3C shows the reconstructed image obtained by the present invention by using 64 pictures like the one illustrated in Figure 3B. It can be seen that substantially all of the spatial details contained within the input picture are reconstructed in the image of Figure 3C.

Reference is now made to Figures 4A - 4D, which further illustrate the results of computer simulations of a preferred embodiment of the present invention, as applied to CCD cameras. Figure 4A shows a low resolution image captured from the input picture illustrated in Figure 3A, using a CCD camera having a spatial resolution of 32 x 32 pixels and a color depth of 1 bit per pixel. It can be seen that the image shown in Figure 4A is a black and white image. Figure 4B shows the reconstructed image obtained by the present invention by using 64 pictures like the one illustrated in Figure 4A. It can be seen

that although Figure 4B is not identical to Figure 3A, it nevertheless is a much better approximation than is Figure 4A, both in terms of spatial resolution and in terms of dynamic color range.

Similarly, Figure 4C shows a low resolution image captured from the input picture illustrated in Figure 3A, using a CCD camera having a spatial resolution of 32 x 32 pixels and a color depth of 2 bits per pixel. It can be seen that the image shown in Figure 4C is comprised of four colors. Figure 4D shows the reconstructed image obtained by the present invention, by using 64 pictures like the one illustrated in Figure 4C. It can be seen that Figure 4D is almost identical to Figure 3A.

When the present invention was applied to a CCD camera having a spatial resolution of 32 x 32 pixels and a color depth of 4 bits per pixel (not shown), the reconstructed image (not shown) was indistinguishable from the original.

Reference is now made to Figures 5A – 5C, which illustrates the results of computer simulations of a preferred embodiment of the present invention, as applied to barcode readers. Shown in Figure 5A is an original barcode. Shown in Figure 5B is the image captured by a bar code reader. As a result of the limited resolving capability of the barcode reader, the captured image shown in Figure 5B is substantially different from the barcode shown in Figure 5A. Shown in Figure 5C is a reconstructed image of the barcode using the present invention, based on eight vertical replications. A comparison between Figure 5A and Figure 5C indicates that the present invention successfully overcomes the limitations of conventional barcode readers in resolving scanned barcodes.

The present specification describes the process for acquiring multiple low resolution images from a single picture, and the way to combine the multiple low resolution image data to generate a high resolution image.

Conventions and Notation

In the ensuing description it is assumed that a sensing device samples an object being acquired in lines, such as horizontal lines, using N pixels per line. The present invention is preferably applied separately in two dimensions, such as in a horizontal dimension and a vertical dimension, to increase the pixel resolutions in each of the dimensions. Since the applications of the present invention in each of the dimensions are similar, for the sake of clarity and definiteness the present specification describes a preferred embodiment of the present invention in a single dimension, such as a horizontal dimension. In

particular, rather than use two coordinates (x, y) in the discussion below, a single x coordinate is used, and rather than work with double integrals and double sums, single integrals and single sums are used. Similarly, two-dimensional doubly periodic masking of a two-dimensional array of detectors in a sensing panel is described hereinbelow using a one-dimensional periodic masking function $m(x)$.

When the sensing device samples a line, the detected energy of the n -th pixel is given by

$$u[n] = \int_{-\infty}^{\infty} u(x + n\Delta x)g(x)dx, \quad n = 0, 1, \dots, N-1, \quad (1)$$

where $u(x)$ denotes the captured object along a specific line, Δx denotes the pixel width and $g(x)$ denotes the pixel sensitivity (i.e. apodization).

Multiple Image Acquisition

In a preferred embodiment of the present invention, the sensing device samples a line K times, each time with a shift in the captured object relative to the capture device by an amount of $\Delta x / K$. Letting $u_k[n]$ denote the detected energy of the n -th pixel in the k -th sampling, Equation 1 generalizes to

$$u_k[n] = \int_{-\infty}^{\infty} u(x + n\Delta x + k \frac{\Delta x}{K})g(x)dx, \\ n = 0, 1, \dots, N-1; \quad k = 0, 1, \dots, K-1. \quad (2)$$

Together, the various samples $u_k[n]$ provide KN samples given by

$$y[n] = \int_{-\infty}^{\infty} u(x + n \frac{\Delta x}{K})g(x)dx, \quad n = 0, 1, \dots, KN-1. \quad (3)$$

In an preferred embodiment of the present invention, the shifts in successive image acquisitions by $\Delta x / K$ are implemented by using vibrations of the sensing device. For example, the sensing device can be placed on a vibrating platform. The parameters of the vibrations are estimated by vibration sensors or by use of appropriate algorithms. The vibration parameters are used to synchronize the sampling of the object so that the sampling occurs at times when the vibrated sensing device is located at appropriate sub-pixel shifts.

In an alternate embodiment of the present invention, an assembly of one or more rotated mirrors can be used to shift successive fields of view of a sensing device by sub-pixel shifts. The rotated mirrors reflect the scene to the sensing device.

In yet another embodiment, the shifts in successive image acquisitions by $\Delta x / K$ can be implemented using an optical element instead of the imaging lens of the sensing device. The optical element is attached to the aperture

of the sensing device, and serves like a grating to create replicated views of an object. Typically gratings result in replicas since the Fourier transform of a grating is an impulse train of delta functions. This embodiment using an optical element to create replicated views is particularly well suited for objects that are sufficiently small so that the replicas do not overlap.

The abovementioned optical element can be designed, for example, by a multi-facet lens. It can also be designed by an algorithm such as the one described in Z. Zalevsky, D. Mendlovic and A. W. Lohmann, Gerchberg-Saxton algorithm applied in the fractional Fourier or the Fresnel domain, Optical Letters 21, 1996, pages 842 – 844, the contents of which are hereby incorporated by reference.

It should be apparent to those skilled in the art that it is not necessary that the multiple acquired images be separated by identical sub-pixel shifts. The present invention applies to multiple acquired images separated by sub-pixel shifts of arbitrary sizes. Moreover, successive shifts between acquired images do not have to be sub-pixel. The shifts can be larger than one pixel shifts, as long as the multiple acquired images are all non-integral pixel shifts from one another. Specifically, the relative shifts of the multiple acquired images with reference to a fixed origin can be set to values $r_0\Delta x, r_1\Delta x, \dots, r_{K-1}\Delta x$, as long as the differences $r_i - r_j$ are non-integral for any distinct indices i and j . The case of equal sub-pixel shifts described above corresponds to $r_k = k / K$.

Reference is now made to Figure 6, which illustrates three samplings of an object by a sensing device, separated by sub-pixel shifts, in accordance with a preferred embodiment of the present invention. The object is indicated by a curve $u(x)$, denoted by reference numeral 610. The curve $u(x)$ denotes the color of the object along a line, as a function of position, x . Also indicated in Figure 6 is a curve $g(x)$ denoting the sensitivity of a pixel, denoted by reference numeral 620. The curve $g(x)$ is a characteristic of the sensing device, and indicates how color values are localized by averaging.

Each row in Figure 6 indicates a sampling. The first row samples the object $u(x)$ at positions indicated by dashed vertical lines 630. The six pixel values are denoted by $u_0[0], u_0[1], \dots, u_0[5]$. The second row samples the object $u(x)$ at shifted positions indicated by dashed vertical lines 640. The six pixel values are denoted by $u_1[0], u_1[1], \dots, u_1[5]$. The third row samples the object $u(x)$ at shifted positions indicated by dashed vertical lines 650. The six pixel values are denoted by $u_2[0], u_2[1], \dots, u_2[5]$.

The samplings indicated by the second and third rows is often referred to as "sub-pixel" sampling, since these samplings are centered at fractional pixel locations. Specifically, in Figure 6, the samples in the second row are centered at the one-third pixel locations, and the samples in the third row are centered at the two-thirds pixel locations. The value of K for the geometry illustrated in Figure 6 is $K = 3$. The three sets of samples together form the eighteen samples $y[0] = u_0[0]$, $y[1] = u_1[0]$, $y[2] = u_2[0]$, $y[3] = u_0[1]$, ..., $y[17] = u_2[5]$, form the full set of samples at all of the pixel thirds locations. These eighteen samples $y[n]$ are used to reconstruct the values $u(0)$, $u(\frac{\Delta x}{3})$, $u(\frac{2\Delta x}{3})$, ..., $u(\frac{17\Delta x}{3})$ of the object $u(x)$.

The present invention uses the samples $y[n]$ to approximately reconstruct the values of $u(n\frac{\Delta x}{K})$. Determining these reconstructed values achieves super-resolution with a resolution enhancement factor of K , since the sensing device has a resolution of N pixels per line, and the reconstructed signal has KN pixels per line.

In order to describe the reconstruction of the values $u(n\frac{\Delta x}{K})$ from the samples $y[n]$, a classical result from signal processing is used, which relates the discrete Fourier transform of a sampled analog signal to the continuous Fourier transform of the analog signal.

A Bit of History: Frequency Representation of Sampling

In the ensuing description, $s(t)$ is used to denote a continuous time signal, and $S(j\Omega)$ is used to denote its continuous-time Fourier transform, defined by:

$$S(j\Omega) = \int_{-\infty}^{\infty} s(t)e^{-j\Omega t} dt . \quad (4)$$

Periodic sampling of $s(t)$ with a sampling period of T produces a discrete time signal $s[n]$, defined by:

$$s[n] = s(nT) . \quad (5)$$

The discrete-time Fourier transform of $s[n]$ is denoted by $S(e^{j\omega})$, and is defined by:

$$S(e^{j\omega}) = \sum_{n=-\infty}^{\infty} s[n]e^{-j\omega n} . \quad (6)$$

An age-old result, referred to as the Poisson Summation Formula and which is one of the most prominent formulas used in discrete signal

processing, provides a relationship between the continuous-time Fourier transform $S(j\Omega)$ of a continuous time signal and the discrete-time Fourier transform $S(e^{j\omega})$ of the sampled signal. Specifically, the Poisson Summation Formula states that

$$\sum_{n=-\infty}^{\infty} s(nT) = \frac{1}{T} \sum_{k=-\infty}^{\infty} S(-j \frac{2\pi k}{T}) . \quad (7)$$

In fact, more generally the Poisson Summation Formula establishes that

$$\sum_{n=-\infty}^{\infty} s(t + nT) = \frac{1}{T} \sum_{k=-\infty}^{\infty} S(-j \frac{2\pi k}{T}) e^{-j \frac{2\pi k t}{T}} , \quad (8)$$

of which Equation 7 above is a special case corresponding to $t = 0$.

A simple proof of Equation 8, as indicated on page 210 of Rudin, W., "Real and Complex Analysis: Second Edition," McGraw-Hill, 1974, is as follows. The function $f(t)$ defined by

$$f(t) = \sum_{n=-\infty}^{\infty} s(t + nT) \quad (9)$$

is a periodic function with period T . As such, it has a standard Fourier series expansion of the form

$$f(t) = \sum_{k=-\infty}^{\infty} c_k e^{-j \frac{2\pi k t}{T}} , \quad (10)$$

where the Fourier coefficient c_k is given by

$$c_k = \frac{1}{T} \int_0^T f(t) e^{j \frac{2\pi k t}{T}} dt . \quad (11)$$

Upon substituting Equation 9 into Equation 11 it can be seen that

$$c_k = \frac{1}{T} \int_{-\infty}^{\infty} s(t) e^{j \frac{2\pi k t}{T}} dt = \frac{1}{T} S(-j \frac{2\pi k}{T}) , \quad (12)$$

from which Equation 8 follows when Equation 12 is substituted back into Equation 10.

If the function $s(t) e^{-j \frac{\omega t}{T}}$ is used in Equation 8, instead of the function $s(t)$, one obtains the result

$$\sum_{n=-\infty}^{\infty} s(t + nT) e^{-j \frac{\omega t}{T}} = \frac{e^{j \frac{\omega t}{T}}}{T} \sum_{k=-\infty}^{\infty} S(j \frac{\omega - 2\pi k}{T}) e^{-j \frac{2\pi k t}{T}} . \quad (13)$$

By setting $t = 0$ in Equation 13 one arrives at the familiar sampling equation

$$S(e^{j\omega}) = \frac{1}{T} \sum_{k=-\infty}^{\infty} S(j \frac{\omega - 2\pi k}{T}) , \quad (14)$$

which appears as Equation 3.20 in A. V. Oppenheim and R. W. Schaffer, "Discrete-Time Signal Processing," Prentice Hall, 1989. Equation 14 indicates that the discrete Fourier transform of a sampled analog signal is comprised of periodically repeated copies of the continuous Fourier transform of the analog

signal. The copies are shifted by integer multiples of the sampling frequency and superimposed. Equation 14 is often expressed in terms of delta functions; namely, that the Fourier transform of an impulse train $\sum_{n=-\infty}^{\infty} \delta(t - nT)$ is itself an impulse train $\frac{2\pi}{T} \sum_{k=-\infty}^{\infty} \delta(\Omega - \frac{2\pi k}{T})$.

It is noted that Equation 14 can also be derived directly from Equation 7 by using $s(t)e^{-j\frac{\omega t}{T}}$ instead of $s(t)$.

For values of ω that are small enough to avoid significant aliasing in Equation 14, say $\omega < \Omega_s$, one can approximate the sums on the right hand sides of Equations 13 and 14 by the term with $k = 0$. When this approximation is made, it in turn leads to the approximation

$$\sum_{n=-\infty}^{\infty} s(t + nT)e^{-j\omega n} \approx S(e^{j\omega})e^{j\frac{\omega t}{T}}, \quad \left| \frac{\omega}{T} \right| < \Omega_s. \quad (15)$$

It is noted that as the sampling period, T , decreases, the approximation in Equation 15 becomes more accurate. The increase in accuracy is due to the fact that the aliasing, or overlap, between the copies on the right hand sides of Equations 13 and 14 decreases, since the shifts $\frac{2\pi}{T}$ between copies increase.

The present invention uses a version of Equation 15 to obtain super-resolution. Specifically, instead of sampling $s[n] = s(nT)$ as in Equation 5, the sampling is done through an integral

$$y[n] = \int_{-\infty}^{\infty} s(t + nT)g(t)dt, \quad (16)$$

where $g(t)$ represents the sensitivity, or apodization, of a pixel. Multiplying both sides of Equation 15 by $g(t)$ and integrating, results in

$$Y(e^{j\omega}) \approx S(e^{j\omega})G(-j\frac{\omega}{T}), \quad \left| \frac{\omega}{T} \right| < \Omega_s, \quad (17)$$

which is the form used in the present invention.

Referring back to Equation 3, it follows from Equation 17, upon replacing T by $\frac{\Delta x}{K}$, that

$$U(e^{j\omega}) \approx \frac{Y(e^{j\omega})}{G(-j\frac{\omega K}{\Delta x})}, \quad \left| \frac{\omega K}{\Delta x} \right| < \Omega_s, \quad (18)$$

where $U(e^{j\omega})$ is the discrete Fourier transform of the samples $u(n\frac{\Delta x}{K})$, sought to be reconstructed; namely,

$$U(e^{j\omega}) = \sum_{n=-\infty}^{\infty} u(n \frac{\Delta x}{K}) e^{-j\omega n} . \quad (19)$$

The Fourier transform $Y(e^{j\omega})$ is known from the samples $y[n]$ in Equation 3, and the Fourier transform $G(-j \frac{\omega K}{\Delta x})$ is determined from knowledge of the sensitivity function $g(x)$. It is noted that as K increases, the approximation in Equation 18 becomes more accurate.

Regarding the Fourier transform $Y(e^{j\omega})$, the values of $y[n]$ set forth in Equation 3 above are only defined for indices $n = 0, 1, \dots, KN-1$. For indices n outside of this range, $y[n]$ is preferably defined to be zero. With such a convention, the Fourier transform $Y(e^{j\omega})$ is given by the finite sum

$$Y(e^{j\omega}) = \sum_{n=0}^{KN-1} y[n] e^{-j\omega n} . \quad (20)$$

In a preferred embodiment, the present invention uses Equation 18 to determine the Fourier transform $U(e^{j\omega})$, and then reconstructs the values $u(n \frac{\Delta x}{K})$, $n = 0, 1, \dots, KN-1$, from $U(e^{j\omega})$ by using an inverse discrete Fourier transform. Preferably a Fast Fourier Transform (FFT), as is familiar to those skilled in the art, is used to invert the spectral values $U(e^{j\omega})$. The reconstruction is approximate, since Equation 18 is itself only an approximation. Since it is necessary to reconstruct KN values of $u(x)$, it is accordingly necessary to apply Equation 18 at KN frequencies that are spaced $\frac{2\pi}{KN}$ apart one from the next, since the Fourier transform $U(e^{j\omega})$ is periodic with period 2π . In a preferred embodiment of the present invention, Equation 18 is applied at the KN frequencies

$$\omega = \frac{2\pi k}{KN} , \quad k = 0, 1, \dots, KN-1. \quad (21)$$

When the Fourier transform $U(e^{j\omega})$ is inverted it is possible that values of $u(n \frac{\Delta x}{K})$ are non-zero outside of the index range $n = 0, 1, \dots, KN-1$. As it is only the values of $u(n \frac{\Delta x}{K})$ within the index range $n = 0, 1, \dots, KN-1$ that are of interest, the values outside this index range can be ignored.

An apparent difficulty arises in implementing Equation 18 if there are frequencies ω as given in Equation 21, at which $G(-j \frac{\omega K}{\Delta x}) = 0$, since this would entail division by zero at such frequencies.

The function $G(-j\Omega)$ is typically a real-valued function, since the pixel sensitivity function $g(x)$ is typically symmetric about $x = 0$. Since a pixel is

typically more sensitive to light in its central area and less sensitive in its outer regions, the pixel sensitivity function $g(x)$ is typically "bell-shaped," similar to Gaussian functions. In case $g(x)$ happens to be a Gaussian function, its Fourier transform has no zeros, and there no divisions by zero are encountered in implementing Equation 18. However, for other sensitivity functions, such a difficulty can arise.

The present invention avoids such a difficulty by using specially constructed masks, as described hereinbelow.

Masking

In order to avoid division by zero in Equation 18, the present invention preferably employs an optical device to remove zeros of $G(-j\frac{\omega K}{\Delta x})$ that are less than the frequency Ω_s . The frequency Ω_s is the maximal frequency in the reconstructed data.

The present invention preferably attaches a mask in the form of a fine transmission grating with a period of Δx to the sensing device panel. As mentioned hereinabove, the mask under discussion is really a two-dimensional doubly periodic mask that covers a two-dimensional array of detectors. For the sake of clarity and definiteness it is being described as a single dimensional periodic mask, with the understanding that the one-dimensional analysis presented herein applies to each of the two dimensions of the sensing device panel.

Reference is now made to Figure 7, which is a simplified illustration of a mask attached to a sensor panel of array detectors in an image sensing device, in accordance with a preferred embodiment of the present invention. A sensor panel 700 in an image sensing device contains a two-dimensional array of detectors 710. Detectors 710 are depicted as individual cells within sensor panel 700. The array of detectors is periodic, with periodic spacings Δx and Δy in the horizontal and vertical dimensions, respectively. The spacings Δx and Δy correspond to the pixel spacings in the sampled digital image obtained from the image sensing device. A masking pattern 720 in the form of a fine sub-pixel transmission grating is used to generate a doubly periodic mask, with respective periods Δx and Δy in the horizontal and vertical dimensions. In a preferred embodiment of the present invention, the doubly periodic mask is attached to sensor panel 700. Each detector 710 is masked by the same masking pattern 720.

Use of a mask decreases the effective size of each pixel so that the Fourier transform $G(j\Omega)$ of its sensitivity function has a wider band, and its zeros accordingly move to higher frequencies. The apodized pixel, determined by the transmission pattern of the grating, is preferably designed in an iterative manner, as described hereinbelow, so that the bandwidth of the Fourier transform $G(j\Omega)$ of its sensitivity function is wider than the maximal frequency to be reconstructed. Use of a transmission grating has the disadvantage of decreasing the energy sensed at each pixel, since it blocks out some of the illumination.

A mask is described mathematically by a spatial function $m(x)$, preferably taking values 0 and 1. The effect of a mask is to modify the pixel sensitivity function from $g(x)$ to $p(x) = g(x)m(x)$. An objective of choosing a suitable mask is to obtain a function $p(x)$ whose Fourier transform does not have zeroes at frequencies that are between 0 and Ω_s , so that when the Fourier transform $P(-j\frac{\omega K}{\Delta x})$ of the modified pixel sensitivity function $p(x)$ is used in Equation 18 instead of $G(-j\frac{\omega K}{\Delta x})$, there is no division by zero.

A rationale for using a mask to avoid zeroes of G is that typically an effect of a mask is to add frequencies that may have not been present beforehand.

To construct a mask as desired, the present invention preferably uses a grating in the form of a plurality of optically transparent slits.

$$m(x) = 1 - \sum_{i=1}^M \text{rect}\left(\frac{x}{\Delta x_i}\right) \otimes \delta(x - x_i), \quad (22)$$

where M is the total number of slits, x_1, x_2, \dots, x_M are the locations of the slits and Δx_i is the width of the i -th slit. The function $\text{rect}()$ is given by

$$\text{rect}(z) = \begin{cases} 1, & -1/2 < z < 1/2, \\ 0, & \text{otherwise} \end{cases} \quad (23)$$

and \otimes denotes convolution.

Reference is now made to Figure 8, which illustrates the shape of a mask in accordance with Equation 22. Such a mask consists of M slits 810, centered at positions x_1, x_2, \dots, x_M , each having respective widths of Δx_i . Preferably, the value of M is a number between zero and K , and the values Δx_i are each approximately equal to the sub-pixel size $\Delta x / K$. As can be seen in Figure 8, the values of the mask $m(x)$ are 0 inside the slits and 1 outside the slits. The total width of the mask is Δx ; namely, the width of a pixel. The mask is intended to affect the shape of $g(x)$ at sub-pixel granularity. In practice, the granularity is discretized to $\Delta x / K$; namely, the sub-pixel shift between successive images

acquired by the image sensing device. For example, referring back to Figure 3C, the mask used in reconstructing the image shown therein is [0 1 0 1 1 0 0 0], each of the eight entries in this array representing a sub-pixel size of one eighth of a pixel. Thus the function $m(x)$ for the mask used in Figure 3C is given for $0 \leq x < \Delta x$ by

$$m(x) = \begin{cases} 1, & \frac{1}{8}\Delta x \leq x < \frac{2}{8}\Delta x, \text{ or } \frac{3}{8}\Delta x \leq x < \frac{5}{8}\Delta x \\ 0, & \text{otherwise} \end{cases} \quad (24)$$

The sensitivity function of each masked pixel is given by

$$p(x) = g(x)m(x), \quad (25)$$

and it can be seen that the Fourier transform of $p(x)$ is given by

$$\begin{aligned} P(j\Omega) &= P(j\Omega; x_1, x_2, \dots, x_M; \delta x_1, \delta x_2, \dots, \delta x_M) = \\ &= G(j\Omega) - \sum_{i=1}^M \delta x_i G(j\Omega) \otimes [e^{-j\Omega x_i} \text{sinc}(\frac{1}{2}\Omega \delta x_i)] , \end{aligned} \quad (26)$$

where $\text{sinc}(z)$ denotes the function $\text{sinc}(z) = \frac{\sin z}{z}$.

Preferably, to determine an optimal mask, a predetermined value of M is selected, and a search is made for position values x_1, x_2, \dots, x_M and widths $\delta x_1, \delta x_2, \dots, \delta x_M$ for which the $|P(j\Omega)|$ is bounded away from zero as much as possible. Specifically, define

$$\begin{aligned} \sigma(x_1, x_2, \dots, x_M; \delta x_1, \delta x_2, \dots, \delta x_M) &= \\ &= \min_{\Omega \leq \Omega_s} |P(j\Omega; x_1, x_2, \dots, x_M; \delta x_1, \delta x_2, \dots, \delta x_M)| , \end{aligned} \quad (27)$$

where Ω_s denotes the frequency up to which no significant aliasing occurs, as defined above. Then optimal values for x_1, x_2, \dots, x_M and $\delta x_1, \delta x_2, \dots, \delta x_M$ are preferably determined by

$$\begin{aligned} (x_1, x_2, \dots, x_M; \delta x_1, \delta x_2, \dots, \delta x_M) &= \\ &= \arg\text{-max} \sigma(x_1, x_2, \dots, x_M; \delta x_1, \delta x_2, \dots, \delta x_M) , \end{aligned} \quad (28)$$

where $\arg\text{-max}$ denotes the arguments x_1, x_2, \dots, x_M and $\delta x_1, \delta x_2, \dots, \delta x_M$ which maximize the function σ .

The search range over which optimal values of x_1, x_2, \dots, x_M and $\delta x_1, \delta x_2, \dots, \delta x_M$ are sought is such that the total $\delta x_1 + \delta x_2 + \dots + \delta x_M$ of all the widths does not exceed the pixel width Δx . Additionally, each individual width δx_i must not be less than 2λ , where λ is the wavelength of the incoming light – otherwise, the light will not be affected by the mask. Moreover, construction of a mask and attaching it to the detectors may further limit the widths δx_i to exceed a minimum value of δx_{\min} .

From energy considerations, it is clear that on the one hand, it is desirable that each width δx_i be as small as possible, since δx_i is proportional to

the energy blocked by the mask. On the other hand, this must be traded off against the condition that $|P(j\Omega)|$ be bounded away from zero.

Specifically, if E_t denotes the total light energy for a typical viewing target, when viewed without a mask, then the energy detected when a mask is present is given by

$$E = E_t \left(1 - \frac{\sum_{i=1}^M \delta x_i}{\Delta x}\right), \quad (29)$$

since the energy blocked by the slits of the mask is proportional to the total width of the slits combined.

Thus for a given minimum energy E_{min} , required to activate the detectors, the widths δx_i are constrained to satisfy

$$\sum_{i=1}^M \delta x_i \leq \left(1 - \frac{E_{min}}{E_t}\right) \Delta x. \quad (30)$$

Condition (30), together with the condition that $\delta x_i \geq \delta x_{min}$, for $i = 1, 2, \dots, M$, determine the search range for widths $\delta x_1, \delta x_2, \dots, \delta x_M$ over which a maximum of $\sigma(x_1, x_2, \dots, x_M; \delta x_1, \delta x_2, \dots, \delta x_M)$ is sought.

When values of x_1, x_2, \dots, x_M and $\delta x_1, \delta x_2, \dots, \delta x_M$ are determined according to Equation 28, Equation 22 is used to generate an optimal mask.

In an alternative embodiment of the present invention, rather than maximize $\sigma(x_1, x_2, \dots, x_M; \delta x_1, \delta x_2, \dots, \delta x_M)$, the values of x_1, x_2, \dots, x_M and $\delta x_1, \delta x_2, \dots, \delta x_M$ are determined by maximizing a weighted function $\sigma(x_1, x_2, \dots, x_M; \delta x_1, \delta x_2, \dots, \delta x_M) w(\delta x_1, \delta x_2, \dots, \delta x_M)$, where w is an appropriate weight function. For example, w can put higher weight on smaller values of the widths δx_i , so that preference is given to masks having slits with smaller widths.

Reference is now made to Figures 9A – 9J, which illustrate the use of a mask in obtaining super-resolution, in accordance with a preferred embodiment of the present invention. Figure 9A illustrates an input object, such as a barcode, represented as a function $u(x)$. Figure 9B illustrates the Fourier transform of $u(x)$. Figure 9C illustrates a pixel sensitivity function $g(x)$. Figure 9D illustrates the Fourier transform of $g(x)$.

Figure 9E illustrates conventional sampling of $u(x)$ as a digital signal, without using super resolution enhancement. Figure 9F illustrates the Fourier transform of the digital signal of Figure 9E. Figure 9G illustrates sampling of $u(x)$ as a digital signal with a resolution eight times higher than the sampling illustrated in Figure 9E. Figure 9H illustrates the Fourier transform of

the digital signal of Figure 9G. Figure 9I illustrates a mask used in accordance with a preferred embodiment of the present invention.

Figure 9J illustrates the Fourier transform of a masked pixel, using the mask of Figure 9I. By comparing Figure 9D with Figure 9J it can be seen that the spectrum of the masked pixel does not contain zeros within the region displayed. It can further be seen that an effect of the masking is to expand the spectrum of $g(x)$.

Reference is now made to Figure 10, which illustrates an enhanced image obtained by applying super-resolution to the low resolution CCD captured image illustrated in Figure 3B, without the use of a mask. As can be seen in Figure 10, artifacts in the form of vertically oriented white stripes arise due to the presence of zeroes of $G(-j\frac{\omega K}{\Delta x})$. When a mask is applied in accordance with a preferred embodiment of the present invention, the zeroes of $G(-j\frac{\omega K}{\Delta x})$ are removed, and the result obtained is the image shown in Figure 3C. It may thus be appreciated that the use of a mask serves to remove the artifacts indicated in Figure 10.

Improved Approximation

As explained hereinabove, the approximation in Equation 18 is based on the assumption that ω is small enough to avoid aliasing in Equation 14. A more accurate approximation can be made by taking into consideration the aliasing between adjacent copies of S in the right-hand side of Equation 14. However, in order to obtain the increase in accuracy, it is necessary to increase the sampling rate.

It is appreciated by those skilled in the art that the assumption that aliasing between copies of S in Equation 14 is due to overlap between adjacent terms $S(j\frac{\omega}{T})$ and $S(j\frac{\omega \pm 2\pi}{T})$ is equivalent to the assumption that reduction of the sampling period from T to $T/2$ removes aliasing. Moreover, the information at frequency ω in the discrete Fourier transform of a signal sampled with sampling period T corresponds with the information at both frequencies $\omega/2$ and $\omega/2 + \pi$ in the discrete Fourier transform of the signal sampled with sampling period $T/2$. A precise formulation of this relationship appears in the above referenced Oppenheim and Schaffer as Equation 3.76, which describes a frequency-domain relationship between the input and the output of a sampling rate compressor ("downsampling").

These observations above are a basis for an improved approximation used in accordance with a preferred embodiment of the present invention, as described hereinbelow. Specifically, replace the sampling period, T , by $T/2$ in Equation 16:

$$y[n] = \int_{-\infty}^{\infty} s(t + n\frac{T}{2})g(t)dt . \quad (31)$$

Under the assumption that aliasing in Equation 14 is due to overlap between adjacent terms $S(j\frac{\omega}{T})$ and $S(j\frac{\omega \pm 2\pi}{T})$, the approximation to $S(e^{j\omega})$ becomes

$$S(e^{j\omega}) \approx \frac{1}{T}S(j\frac{\omega}{T}) + \frac{1}{T}S(j\frac{\omega - 2\pi}{T}) , \quad 0 < \omega < \pi , \quad (32)$$

for positive values of ω , and

$$S(e^{j\omega}) \approx \frac{1}{T}S(j\frac{\omega}{T}) + \frac{1}{T}S(j\frac{\omega + 2\pi}{T}) , \quad -\pi < \omega < 0 , \quad (33)$$

for negative values of ω .

Using similar analysis to that embodied in Equations 13 - 18, it can be shown that

$$U(e^{j\omega}) \approx \frac{1}{2} \left[Y(e^{j\frac{\omega}{2}}) / G(-j\frac{\omega K}{\Delta x}) + Y(e^{j\frac{\omega - 2\pi}{2}}) / G(-j\frac{(\omega - 2\pi)K}{\Delta x}) \right] , \quad 0 < \omega < \pi , \quad (34)$$

for positive values of ω , and

$$U(e^{j\omega}) \approx \frac{1}{2} \left[Y(e^{j\frac{\omega}{2}}) / G(-j\frac{\omega K}{\Delta x}) + Y(e^{j\frac{\omega + 2\pi}{2}}) / G(-j\frac{(\omega + 2\pi)K}{\Delta x}) \right] , \quad -\pi < \omega < 0 , \quad (35)$$

for negative values of ω . Equations 34 and 35 determine $U(e^{j\omega})$ more accurately than Equation 18, since they incorporate aliasing between adjacent copies of S in the sampling representation for $S(e^{j\omega})$. However, they require sub-pixel shifts of $\frac{\Delta x}{2K}$ between successively captured images. This corresponds to a factor of $2K$ increase in data acquisition, whereas the resolution is only enhanced by a factor of K .

An alternative approach to improving the approximation in Equation 18 by taking into consideration the aliasing between adjacent copies of S in the right-hand side of Equation 14, uses an alternating ("checkerboard") mask geometry. As mentioned hereinabove, the above discussion is based on use of a periodic mask, with a period of Δx . By using instead a mask with a period of $2\Delta x$, one effectively generates two pixel sensitivity functions, $g_1(x)$ and $g_2(x)$, where $g_1(x)$ applies to even-numbered detectors and $g_2(x)$ applies to odd-numbered

detectors. Specifically, $g_1(x)$ corresponds to $g(x)m(x)$ and $g_2(x)$ corresponds to $g(x)m(x+\Delta x)$, where $g(x)$ is the pixel sensitivity function for the image sensing device and $m(x)$ is the overall mask. Unlike the above case where the mask has a period of Δx , when the mask has a period of $2\Delta x$ there are effectively two masks operating (namely, the mask itself and the mask shifted by Δx), and consequently the even and odd-numbered pixels are processed differently.

Reference is now made to Figure 11, which is a simplified illustration of an alternating ("checkerboard") mask attached to a sensor panel of array detectors in an image sensing device, in accordance with a preferred embodiment of the present invention. A sensor panel 1100 in an image sensing device contains a two-dimensional array of detectors 1110. Detectors 1110 are depicted as individual cells within sensor panel 1100. The array of detectors is periodic, with periodic spacings Δx and Δy in the horizontal and vertical dimensions, respectively. The spacings Δx and Δy correspond to the pixel spacings in the sampled digital image obtained from the image sensing device.

In distinction to Figure 7, Figure 11 illustrates two different masking patterns 1120 and 1130 in the form of fine sub-pixel transmission gratings that are arranged in an alternating checkerboard pattern to generate a doubly periodic mask, with respective periods $2\Delta x$ and $2\Delta y$ in the horizontal and vertical dimensions. In a preferred embodiment of the present invention, the doubly periodic mask is attached to sensor panel 1100. The detectors 1110 are alternatively masked by the different masking patterns 1120 and 1130.

When using such a mask, Equation 2 (which is one-dimensional) separates into two equations,

$$u_k[n] = \int_{-\infty}^{\infty} u(x + n\Delta x + k \frac{\Delta x}{K}) g_1(x) dx ,$$

for even values of n ; $k = 0, 1, \dots, K-1$, and (36)

$$u_k[n] = \int_{-\infty}^{\infty} u(x + n\Delta x + k \frac{\Delta x}{K}) g_2(x) dx ,$$

for odd values of n ; $k = 0, 1, \dots, K-1$. (37)

By capturing twice as many images as previously, namely, $2K$ images, each detector moves over a full period of the mask, namely, $2\Delta x$. Consequently, two sequences of the form of Equation 3 are acquired, namely,

$$y_1[n] = \int_{-\infty}^{\infty} u(x + n \frac{\Delta x}{K}) g(x) dx , \quad n = 0, 1, \dots, KN-1, \text{ and } (38)$$

$$y_2[n] = \int_{-\infty}^{\infty} u(x + n \frac{\Delta x}{K}) g(x) dx , \quad n = 0, 1, \dots, KN-1 . \quad (39)$$

In turn, using the same analysis embodied in Equations 13 – 18, one arrives at the two conditions

$$Y_1(e^{j\omega}) \approx \frac{1}{T} S(j\frac{\omega}{T}) G_1(-j\frac{\omega}{T}) + \frac{1}{T} S(j\frac{\omega-2\pi}{T}) G_1(-j\frac{\omega-2\pi}{T}), \quad (40)$$

$$Y_2(e^{j\omega}) \approx \frac{1}{T} S(j\frac{\omega}{T}) G_2(-j\frac{\omega}{T}) + \frac{1}{T} S(j\frac{\omega-2\pi}{T}) G_2(-j\frac{\omega-2\pi}{T}), \quad (41)$$

for positive values of ω , $0 < \omega < \pi$, and

$$Y_1(e^{j\omega}) \approx \frac{1}{T} S(j\frac{\omega}{T}) G_1(-j\frac{\omega}{T}) + \frac{1}{T} S(j\frac{\omega+2\pi}{T}) G_1(-j\frac{\omega+2\pi}{T}), \quad (42)$$

$$Y_2(e^{j\omega}) \approx \frac{1}{T} S(j\frac{\omega}{T}) G_2(-j\frac{\omega}{T}) + \frac{1}{T} S(j\frac{\omega+2\pi}{T}) G_2(-j\frac{\omega+2\pi}{T}), \quad (43)$$

for negative values of ω , $-\pi < \omega < 0$. These equations can be used to solve for the individual copies $S(j\frac{\omega}{T})$ and $S(j\frac{\omega \pm 2\pi}{T})$, and then to recover $S(e^{j\omega})$ from Equations 32 and 33. The final result obtained, expressed in terms of $U(e^{j\omega})$, is

$$U(e^{j\omega}) \approx \left[Y_2(e^{j\omega}) \delta_{\frac{2\pi K}{\Delta x}} G_1(-j\frac{\omega K}{\Delta x}) - Y_1(e^{j\omega}) \delta_{\frac{2\pi K}{\Delta x}} G_2(-j\frac{\omega K}{\Delta x}) \right] / \left[G_2(-j\frac{\omega K}{\Delta x}) \delta_{\frac{2\pi K}{\Delta x}} G_1(-j\frac{\omega K}{\Delta x}) - G_1(-j\frac{\omega K}{\Delta x}) \delta_{\frac{2\pi K}{\Delta x}} G_2(-j\frac{\omega K}{\Delta x}) \right] \quad (44)$$

for positive values of ω , $0 < \omega < \pi$, and

$$U(e^{j\omega}) \approx \left[Y_2(e^{j\omega}) \delta_{\frac{2\pi K}{\Delta x}} G_1(-j\frac{\omega K}{\Delta x}) - Y_1(e^{j\omega}) \delta_{\frac{2\pi K}{\Delta x}} G_2(-j\frac{\omega K}{\Delta x}) \right] / \left[G_2(-j\frac{\omega K}{\Delta x}) \delta_{\frac{2\pi K}{\Delta x}} G_1(-j\frac{\omega K}{\Delta x}) - G_1(-j\frac{\omega K}{\Delta x}) \delta_{\frac{2\pi K}{\Delta x}} G_2(-j\frac{\omega K}{\Delta x}) \right] \quad (45)$$

for negative values of ω , $-\pi < \omega < 0$. In Equations 44 and 45, the terms $\delta_{\psi} G(-j\Omega)$ denote the difference

$$\delta_{\psi} G(-j\Omega) = G(-j\Omega) - G(-j(\Omega - \Psi)). \quad (46)$$

In distinction to the approach using Equations 34 and 35, whereby the improvement in accuracy stems from reducing the sub-pixel sampling shift in half, from $\frac{\Delta x}{K}$ to $\frac{\Delta x}{2K}$, the approach using Equations 42 and 43 obtains improvement in accuracy by acquiring $2K$ sampled images, each shifted by $\frac{\Delta x}{K}$.

Both approaches require collection of sampled data that is $2K$ as much data as in a single image captured by a sensing device. They differ in the types of masks used, and in the relative shifts between the multiple images acquired.

When implemented with full two-dimensional processing, both approaches described hereinabove require $4K^2$ as much data as in a single image

captured by a sensing device, in order to enhance image resolution by a factor of two in each pixel dimension.

Geometric Super Resolution vs. Diffractive Super Resolution

The multiple image acquisition described above and illustrated in Figure 6 is geometric in nature; i.e., it is based on viewing the same spatial information several times, such that in each view the object is shifted by a sub-pixel amount. It can be implemented by shifting positions of the sensing device ("temporal multiplexing") or, equivalently, by shifting fields of view ("spatial multiplexing") using an optical element that replicates views of the object with sub-pixel shifts between the replicas. The resolution of a system limited by geometry corresponds to the detection sampling system; i.e., the resolution of system sensors.

In distinction, multiple image acquisition can also be diffractive in nature. The resolution of a system limited by diffraction corresponds to the finest detail that can pass through the system without being distorted, and is proportional to the size of the aperture in the optical system. Thus the resolution of the human visual system is limited by the extent to which the eyes are open. When an observer squints his eyes, the resolution of a scene being viewed decreases, since the size of the opening is decreased.

For example, resolution enhancement can be implemented by an assembly of two moving rotated gratings, a first grating attached to the object being captured, and a second grating attached to a sensor of the sensing device, and moving in a direction opposite to that of the first grating. Such an assembly can be used to enhance the resolution of a diffractive system, since it effectively increases the size of the aperture in the optical system. The movement of the grating attached to the object encodes its spatial information by a Doppler-like effect, and allows the information to be transmitted through a restricted aperture of an imaging lens. The decoding of the information is obtained from the second grating attached to the sensing device, which moves in a direction opposite to that of the first grating. Such an assembly of two rotated gratings is practical for microscopic applications.

However, in many imaging systems the object is distant from the observer, and attachment of a grating to the object is impractical. When applied to scanning systems such as barcode readers, the present invention preferably simulates attachment of a moving grating to the object by illuminating the object with an illumination having a spatial structure of a grating. The illumination is

shifted with time in order to simulate temporal motion of the grating. A specially designed diffractive optical element is attached to the illumination source so that a grating pattern appears in the object plane. The grating pattern is moved by phase modulating the light source, since linear phase modulations appear as shifts in a far field.

Additional Considerations

In reading the above description, persons skilled in the art will realize that there are many apparent variations that can be applied to the methods and systems described. For example, the integral in Equation 3 may be replaced by a discrete Gabor transform over u with window function g ; namely,

$$y[n] = \sum_p g\left(p \frac{\Delta x}{K}\right) u\left((m-p) \frac{\Delta x}{K}\right) . \quad (47)$$

Similarly, one may use instead a wavelet or Mellin transform, as is well known to persons skilled in the art.

Additionally, the shifts between the multiple images that are acquired by the sensing device are not required to be equal. Furthermore, the shifts between the multiple images are not required to be horizontally or vertically disposed, nor are they required to be disposed in a fixed direction. Wavelet transforms and Mellin transforms are particularly advantageous when dealing with unequal shifts between acquired images.

Additionally, the reconstruction algorithm used in the present invention, for generating a high resolution image from multiple low resolution images, need not be separable. That is, it need not be comprised of horizontal and vertical reconstructions. Rather, the reconstruction algorithm used in the present invention can be a genuine two-dimensional algorithm.

In the foregoing specification, the invention has been described with reference to specific exemplary embodiments thereof. It will, however, be evident that various modifications and changes may be made to the specific exemplary embodiments without departing from the broader spirit and scope of the invention as set forth in the appended claims. Accordingly, the specification and drawings are to be regarded in an illustrative rather than a restrictive sense.

CLAIMS

What is claimed is:

1. A method for enhancing the resolution of an image sensing device, comprising the steps of:
 - attaching a mask to a panel of detectors in an image sensing device;
 - generating multiple fields of view, the multiple fields of view being related to one another by sub-pixel shifts;
 - acquiring multiple images with the image sensing device from the multiple fields of view; and
 - combining the multiple images into an enhanced image of higher pixel resolution than the pixel resolutions of the multiple images.
2. The method of claim 1 wherein the image sensing device is a scanner.
3. The method of claim 2 wherein the image sensing device is a barcode reader.
4. The method of claim 1 wherein the image sensing device is a CCD camera.
5. The method of claim 1 wherein the mask is a fine transmission grating.
6. The method of claim 5 wherein the panel of detectors comprises a periodic array of detectors, and the mask is periodic with period equal to that of the periodic array of detectors.
7. The method of claim 5 wherein the panel of detectors comprises a periodic array of detectors, and the mask is periodic with period twice that of the periodic array of detectors.

8. The method of claim 5 further comprising the step of determining the number of slits, the positions of the slits and the widths of the slits in the fine transmission grating.
9. The method of claim 8 wherein said determining step determines the number of slits, the positions of the slits and the widths of the slits, so that the mask eliminates zeroes in a Fourier transform of a function representing a sensitivity of a pixel, within a prescribed range of frequencies.
10. The method of claim 9 wherein the widths of the slits are constrained so as not to block more than a prescribed fraction of light energy from reaching the detectors.
11. The method of claim 9 wherein the widths of the slits are constrained so as not to be smaller than a prescribed minimum width.
12. The method of claim 9 wherein said determining step uses a weight function specifying relative weights to be placed on values for the widths of the slits.
13. The method of claim 9 wherein the mask is of the form

$$m(x) = 1 - \sum_{i=1}^M \text{rect}\left(\frac{x}{\delta x_i}\right) \otimes \delta(x - x_i) .$$
14. The method of claim 1 wherein said generating step uses natural vibrations of a platform supporting the sensing device.
15. The method of claim 1 wherein said generating step uses at least one mirror to shift fields of view of the image sensing device by sub-pixel shifts.
16. The method of claim 1 wherein said combining step is applied separately to rows and columns of pixel data.

17. The method of claim 16 wherein said combining step uses the approximation

$$U(e^{j\omega}) \approx \frac{Y(e^{j\omega})}{G(-j \frac{\omega K}{\Delta x})},$$

to determine the rows and columns of pixel data of the enhanced image.

18. The method of claim 17 wherein said combining step comprises applying an inverse Fourier transform to values of $U(e^{j\omega})$.

19. The method of claim 16 wherein said combining step uses the approximation

$$U(e^{j\omega}) \approx \frac{1}{2} \left[Y(e^{j\frac{\omega}{2}}) / G(-j \frac{\omega K}{\Delta x}) + Y(e^{j\frac{\omega-2\pi}{2}}) / G(-j \frac{(\omega-2\pi)K}{\Delta x}) \right],$$

$$0 < \omega < \pi,$$

for positive values of ω , and

$$U(e^{j\omega}) \approx \frac{1}{2} \left[Y(e^{j\frac{\omega}{2}}) / G(-j \frac{\omega K}{\Delta x}) + Y(e^{j\frac{\omega+2\pi}{2}}) / G(-j \frac{(\omega+2\pi)K}{\Delta x}) \right]$$

$$-\pi < \omega < 0,$$

for negative values of ω , to determine the rows and columns of pixel data of the enhanced image.

20. The method of claim 19 wherein said combining step comprises applying an inverse Fourier transform to values of $U(e^{j\omega})$.

21. The method of claim 16 wherein said combining step uses the approximation

$$U(e^{j\omega}) \approx \left[Y_2(e^{j\omega}) \delta_{\frac{2\pi K}{\Delta x}} G_1(-j \frac{\omega K}{\Delta x}) - Y_1(e^{j\omega}) \delta_{\frac{2\pi K}{\Delta x}} G_2(-j \frac{\omega K}{\Delta x}) \right] /$$

$$\left[G_2(-j \frac{\omega K}{\Delta x}) \delta_{\frac{2\pi K}{\Delta x}} G_1(-j \frac{\omega K}{\Delta x}) - G_1(-j \frac{\omega K}{\Delta x}) \delta_{\frac{2\pi K}{\Delta x}} G_2(-j \frac{\omega K}{\Delta x}) \right]$$

for positive values of ω , $0 < \omega < \pi$, and

$$U(e^{j\omega}) \approx \left[Y_2(e^{j\omega}) \delta_{\frac{2\pi K}{\Delta x}} G_1(-j \frac{\omega K}{\Delta x}) - Y_1(e^{j\omega}) \delta_{\frac{2\pi K}{\Delta x}} G_2(-j \frac{\omega K}{\Delta x}) \right] /$$

$$\left[G_2(-j \frac{\omega K}{\Delta x}) \delta_{\frac{2\pi K}{\Delta x}} G_1(-j \frac{\omega K}{\Delta x}) - G_1(-j \frac{\omega K}{\Delta x}) \delta_{\frac{2\pi K}{\Delta x}} G_2(-j \frac{\omega K}{\Delta x}) \right]$$

for negative values of ω , $-\pi < \omega < 0$, and wherein the terms $\delta_{\psi} G(-j\Omega)$ denote the difference

$$\delta_{\psi} G(-j\Omega) = G(-j\Omega) - G(-j(\Omega - \Psi)) ,$$

to determine the rows and columns of pixel data of the enhanced image.

22. The method of claim 21 wherein said combining step comprises applying an inverse Fourier transform to values of $U(e^{j\omega})$.
23. The method of claim 1 wherein said combining step uses a Gabor transform.
24. The method of claim 1 wherein said combining step uses a wavelet transform.
25. The method of claim 1 wherein said combining step uses a Mellin transform.
26. A system for enhancing the resolution of an image sensing device, comprising:
 - an image sensing device comprising a panel of detectors;
 - a mask attached to said panel of detectors;
 - a motion generator generating multiple fields of view, the multiple fields of view being related to one another by sub-pixel shifts;
 - image acquisition circuitry housed within said image sensing device acquiring multiple images from the multiple fields of view; and
 - a combiner combining the multiple images into an enhanced image of higher pixel resolution than the pixel resolutions of the multiple images.
27. The system of claim 26 wherein said image sensing device is a scanner.

28. The system of claim 27 wherein said image sensing device is a barcode reader.
29. The system of claim 26 wherein said image sensing device is a CCD camera.
30. The system of claim 26 wherein said mask is a fine transmission grating.
31. The system of claim 30 wherein said panel of detectors comprises a periodic array of detectors, and said mask is periodic with period equal to that of said periodic array of detectors.
32. The system of claim 30 wherein said panel of detectors comprises a periodic array of detectors, and said mask is periodic with period twice that of said periodic array of detectors.
33. The system of claim 30 further comprising a grating generator determining the number of slits, the positions of the slits and the widths of the slits in the fine transmission grating.
34. The system of claim 33 wherein said grating generator determines the number of slits, the positions of the slits and the widths of the slits, so that said mask eliminates zeroes in a Fourier transform of a function representing a sensitivity of a pixel.
35. The system of claim 34 wherein the widths of the slits are constrained so as not to block more than a prescribed fraction of light energy from reaching the detectors.
36. The system of claim 34 wherein the widths of the slits are constrained so as not to be smaller than a prescribed minimum width.

37. The system of claim 34 wherein said grating generator uses a weight function specifying relative weights to be placed on values for the widths of the slits.

38. The system of claim 34 wherein said mask is of the form

$$m(x) = 1 - \sum_{i=1}^M \text{rect}\left(\frac{x}{\Delta x_i}\right) \otimes \delta(x - x_i).$$

39. The system of claim 26 wherein said motion generator uses natural vibrations of a platform supporting the sensing device.

40. The system of claim 26 wherein said motion generator uses at least one mirror to shift fields of view of the image sensing device by sub-pixel shifts.

41. The system of claim 26 wherein said combiner is applied separately to rows and columns of pixel data.

42. The system of claim 41 wherein said combiner uses the approximation

$$U(e^{j\omega}) \approx \frac{Y(e^{j\omega})}{G(-j \frac{\omega K}{\Delta x})},$$

to determine the rows and columns of pixel data of the enhanced image.

43. The system of claim 42 wherein said combiner applies an inverse Fourier transform to values of $U(e^{j\omega})$.

44. The system of claim 41 wherein said combiner uses the approximation

$$U(e^{j\omega}) \approx \frac{1}{2} \left[Y(e^{j\frac{\omega}{2}}) / G(-j \frac{\omega K}{\Delta x}) + Y(e^{j\frac{\omega-2\pi}{2}}) / G(-j \frac{(\omega-2\pi)K}{\Delta x}) \right],$$

$$0 < \omega < \pi,$$

for positive values of ω , and

$$U(e^{j\omega}) \approx \frac{1}{2} \left[Y(e^{j\frac{\omega}{2}}) / G(-j\frac{\omega K}{\Delta x}) + Y(e^{j\frac{\omega+2\pi}{2}}) / G(-j\frac{(\omega+2\pi)K}{\Delta x}) \right]$$

$$-\pi < \omega < 0,$$

for negative values of ω , to determine the rows and columns of pixel data of the enhanced image.

45. The system of claim 44 wherein said combiner comprises applying an inverse Fourier transform to values of $U(e^{j\omega})$.

46. The system of claim 41 wherein said combiner uses the approximation

$$U(e^{j\omega}) \approx \left[Y_2(e^{j\omega}) \delta_{\frac{2\pi K}{\Delta x}} G_1(-j\frac{\omega K}{\Delta x}) - Y_1(e^{j\omega}) \delta_{\frac{2\pi K}{\Delta x}} G_2(-j\frac{\omega K}{\Delta x}) \right] /$$

$$\left[G_2(-j\frac{\omega K}{\Delta x}) \delta_{\frac{2\pi K}{\Delta x}} G_1(-j\frac{\omega K}{\Delta x}) - G_1(-j\frac{\omega K}{\Delta x}) \delta_{\frac{2\pi K}{\Delta x}} G_2(-j\frac{\omega K}{\Delta x}) \right]$$

for positive values of ω , $0 < \omega < \pi$, and

$$U(e^{j\omega}) \approx \left[Y_2(e^{j\omega}) \delta_{\frac{2\pi K}{\Delta x}} G_1(-j\frac{\omega K}{\Delta x}) - Y_1(e^{j\omega}) \delta_{\frac{2\pi K}{\Delta x}} G_2(-j\frac{\omega K}{\Delta x}) \right] /$$

$$\left[G_2(-j\frac{\omega K}{\Delta x}) \delta_{\frac{2\pi K}{\Delta x}} G_1(-j\frac{\omega K}{\Delta x}) - G_1(-j\frac{\omega K}{\Delta x}) \delta_{\frac{2\pi K}{\Delta x}} G_2(-j\frac{\omega K}{\Delta x}) \right]$$

for negative values of ω , $-\pi < \omega < 0$, and wherein the terms $\delta_{\psi} G(-j\Omega)$ denote the difference

$$\delta_{\psi} G(-j\Omega) = G(-j\Omega) - G(-j(\Omega - \Psi)),$$

to determine the rows and columns of pixel data of the enhanced image.

47. The system of claim 46 wherein said combiner comprises applying an inverse Fourier transform to values of $U(e^{j\omega})$.

48. The system of claim 26 wherein said combiner uses a Gabor transform.

49. The system of claim 26 wherein said combiner uses a wavelet transform.

50. The system of claim 26 wherein said combiner uses a Mellin transform.
51. A method for enhancing the resolution of an image sensing device, comprising the steps of:
creating replicas of fields of view using an optical element attached to an image sensing device;
acquiring multiple images with the sensing device from the replicas of fields of view; and
combining the multiple images into an enhanced image of higher pixel resolution than the pixel resolutions of the multiple images.
52. The method of claim 51 wherein the optical element is a diffractive optical element.
53. The method of claim 51 wherein the optical element is a reflective optical element.
54. The method of claim 51 wherein the optical element is a combined diffractive and reflective optical element.
55. The method of claim 51 wherein the optical element produces an effect of a grating.
56. The method of claim 51 wherein the optical element is multifaceted.
57. The method of claim 51 wherein the replicas of fields of views are non-overlapping.
58. A system for enhancing the resolution of an image sensing device, comprising:
an image sensing device;

an optical element attached to said image sensing device, said optical element being such as to create replicas of fields of view;

image acquisition circuitry housed within said image sensing device acquiring multiple images from the replicas of fields of view; and

a combiner combining the multiple images into an enhanced image of higher pixel resolution than the pixel resolutions of the multiple images.

59. The system of claim 58 wherein said optical element is a diffractive optical element.

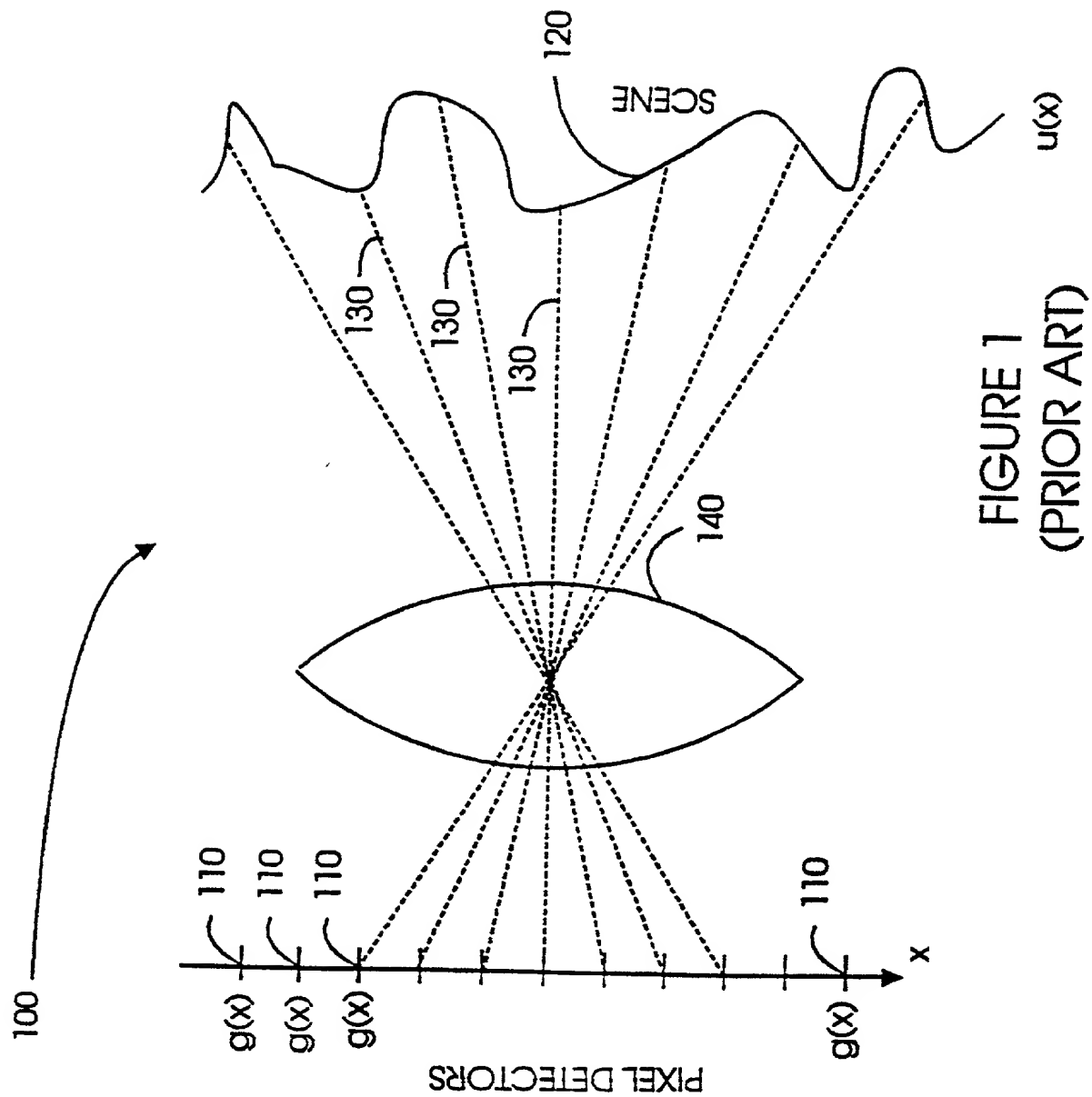
60. The system of claim 58 wherein said optical element is a reflective optical element.

61. The system of claim 58 wherein said optical element is a combined diffractive and reflective optical element.

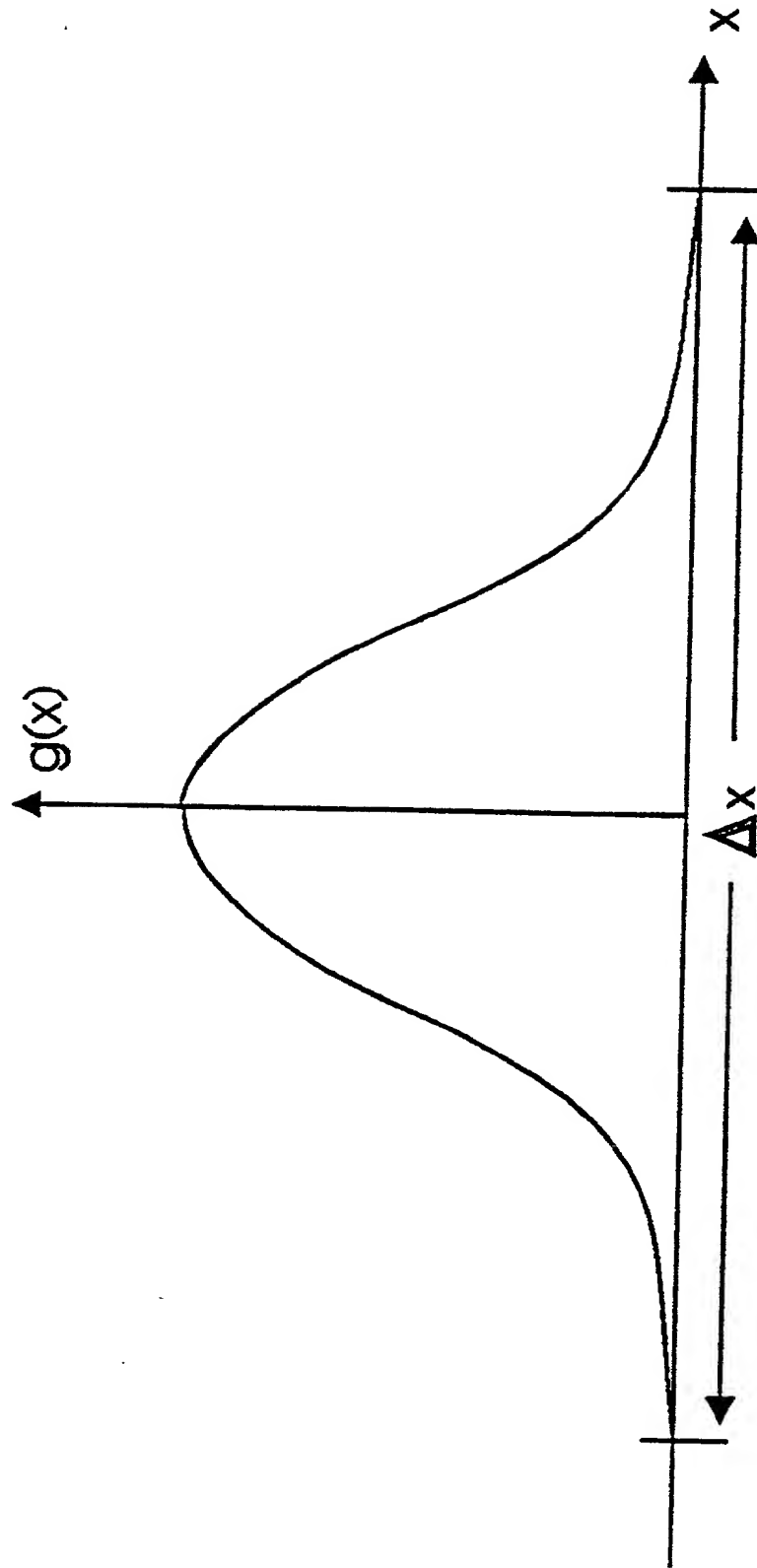
62. The system of claim 58 wherein said optical element produces an effect of a grating.

63. The system of claim 58 wherein said optical element is multifaceted.

64. The system of claim 58 wherein the replicas of fields of view are non-overlapping.

FIGURE 1
(PRIOR ART)

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FIGURE 2
(PRIOR ART)

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FIG. 3A



FIG. 3B

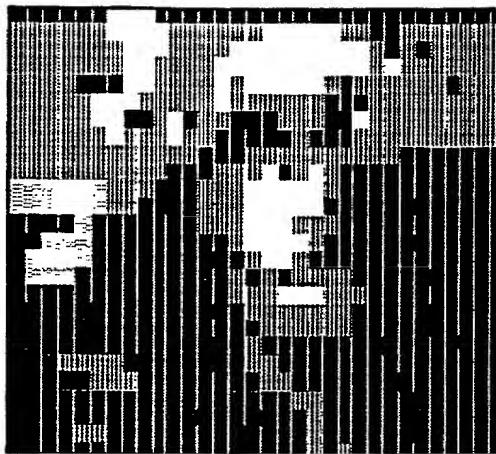


FIG. 3C



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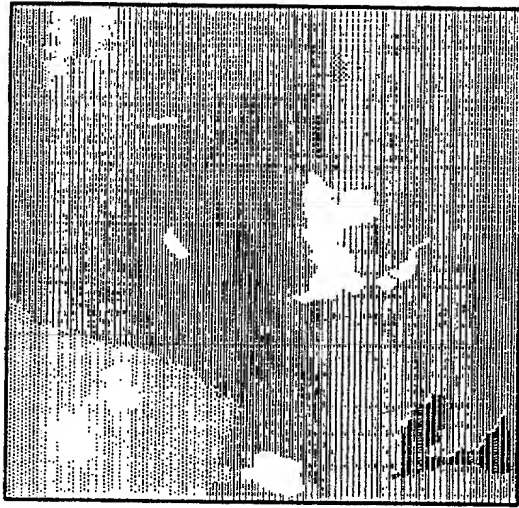


FIG. 4B



FIG. 4D

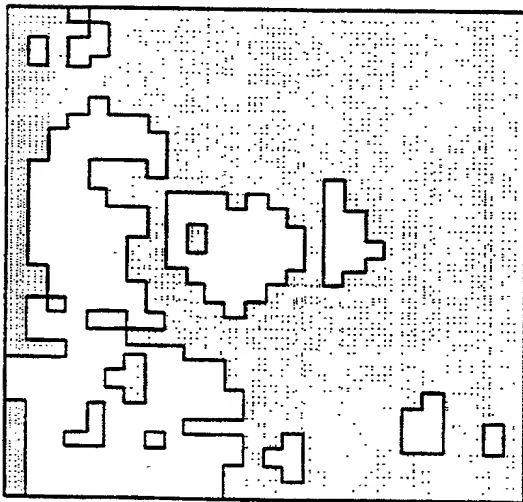


FIG. 4A

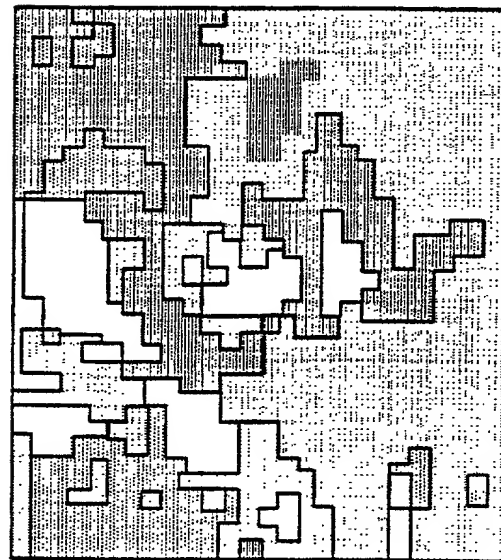


FIG. 4C

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FIG. 5A

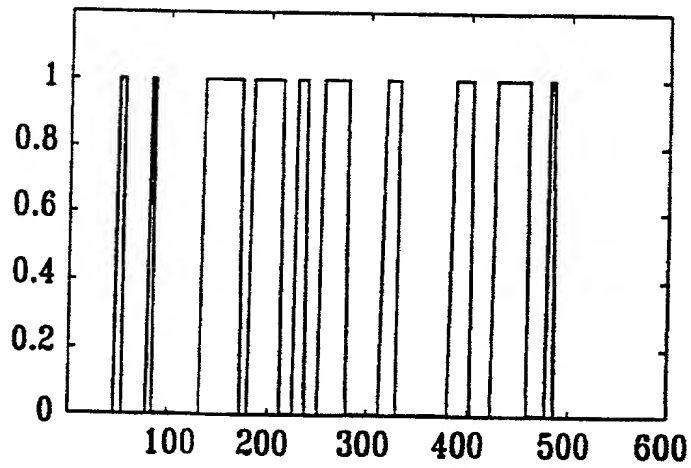


FIG. 5B

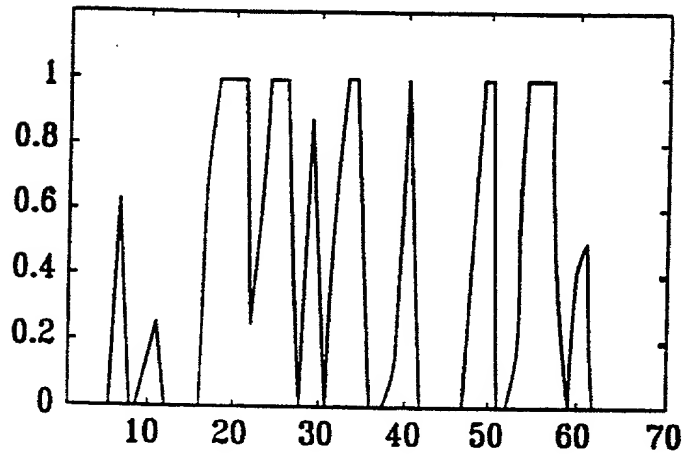
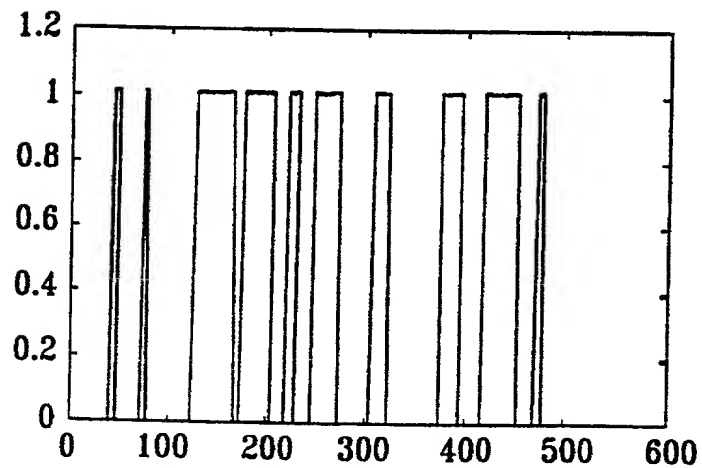


FIG. 5C



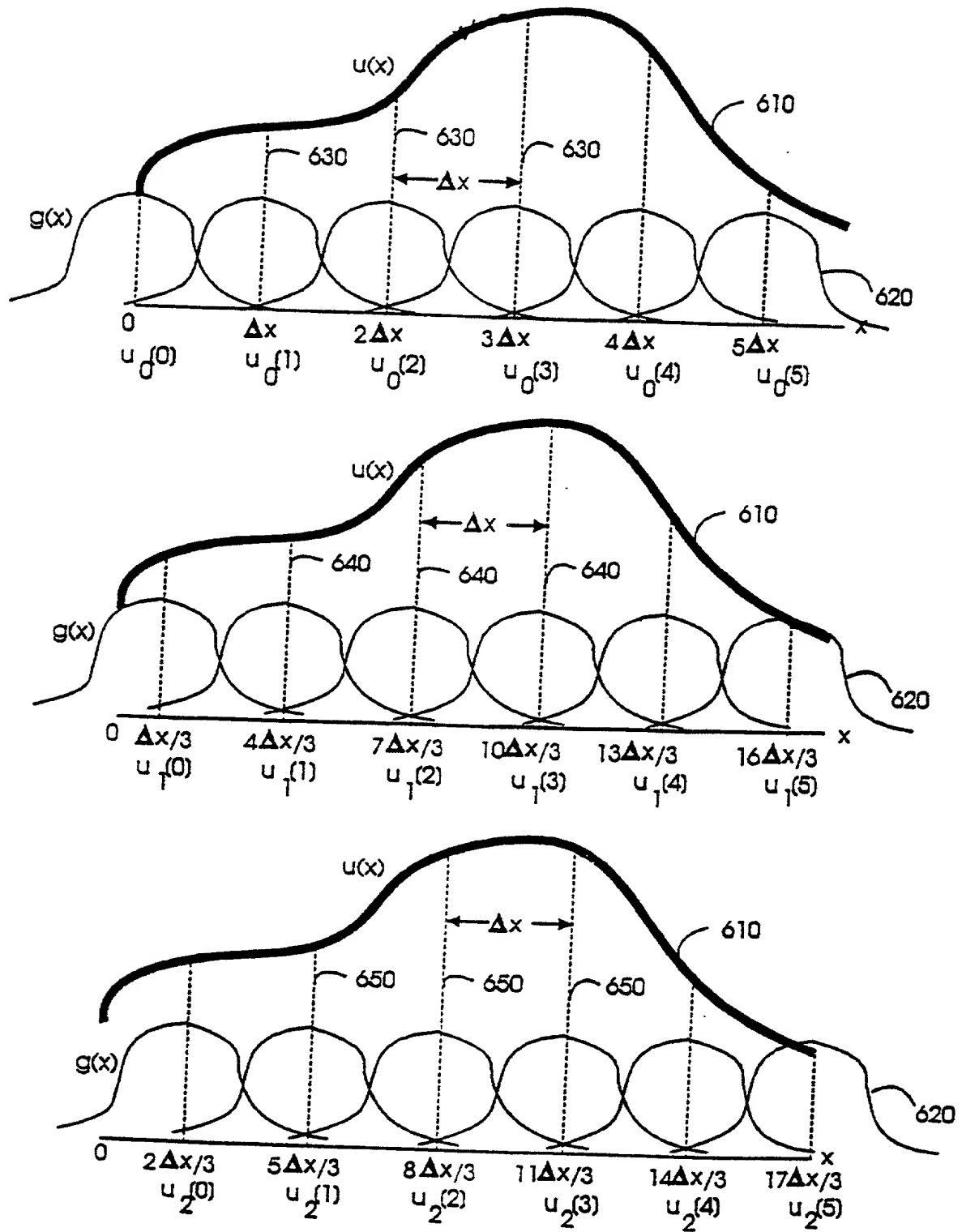


FIGURE 6

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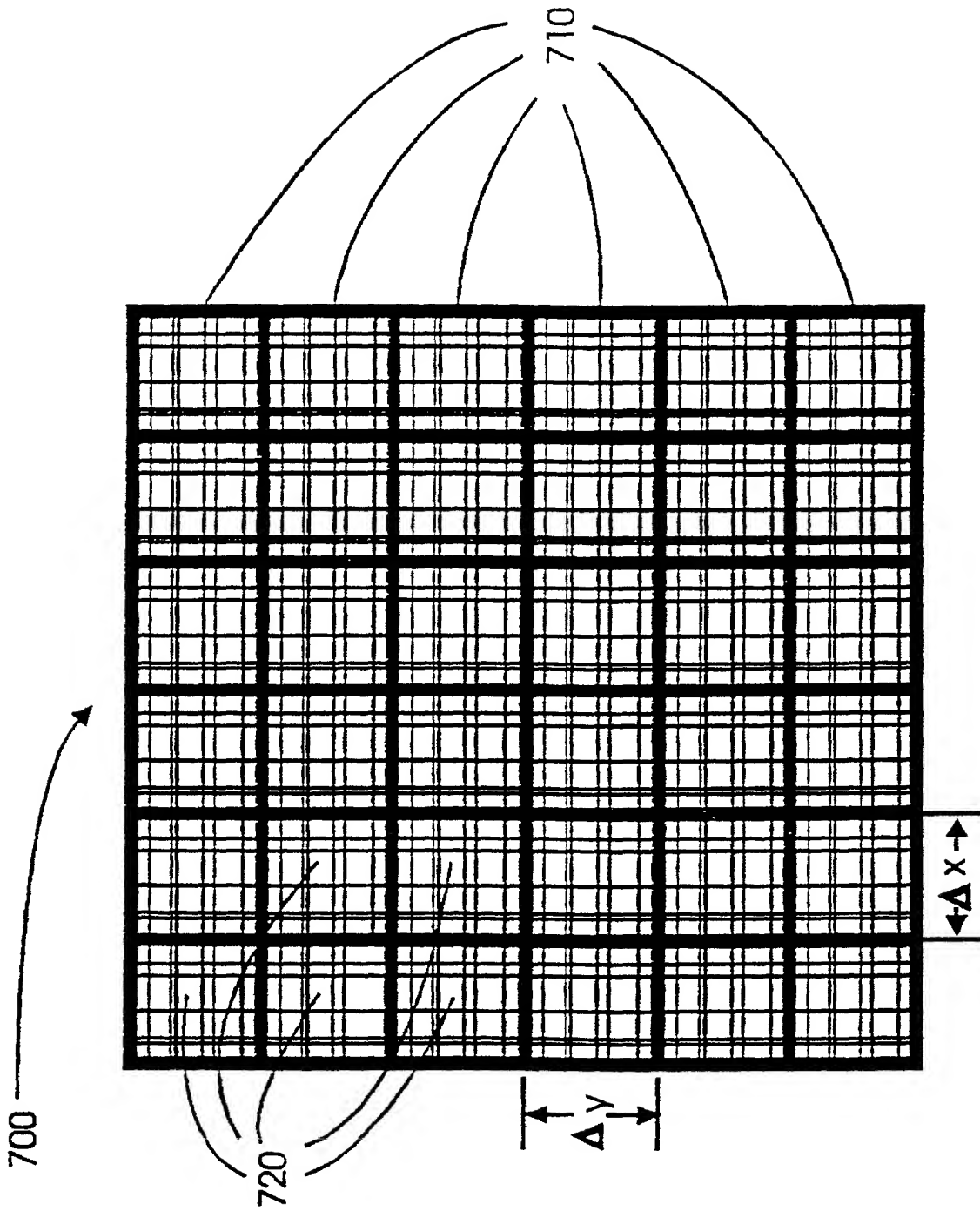


FIGURE 7

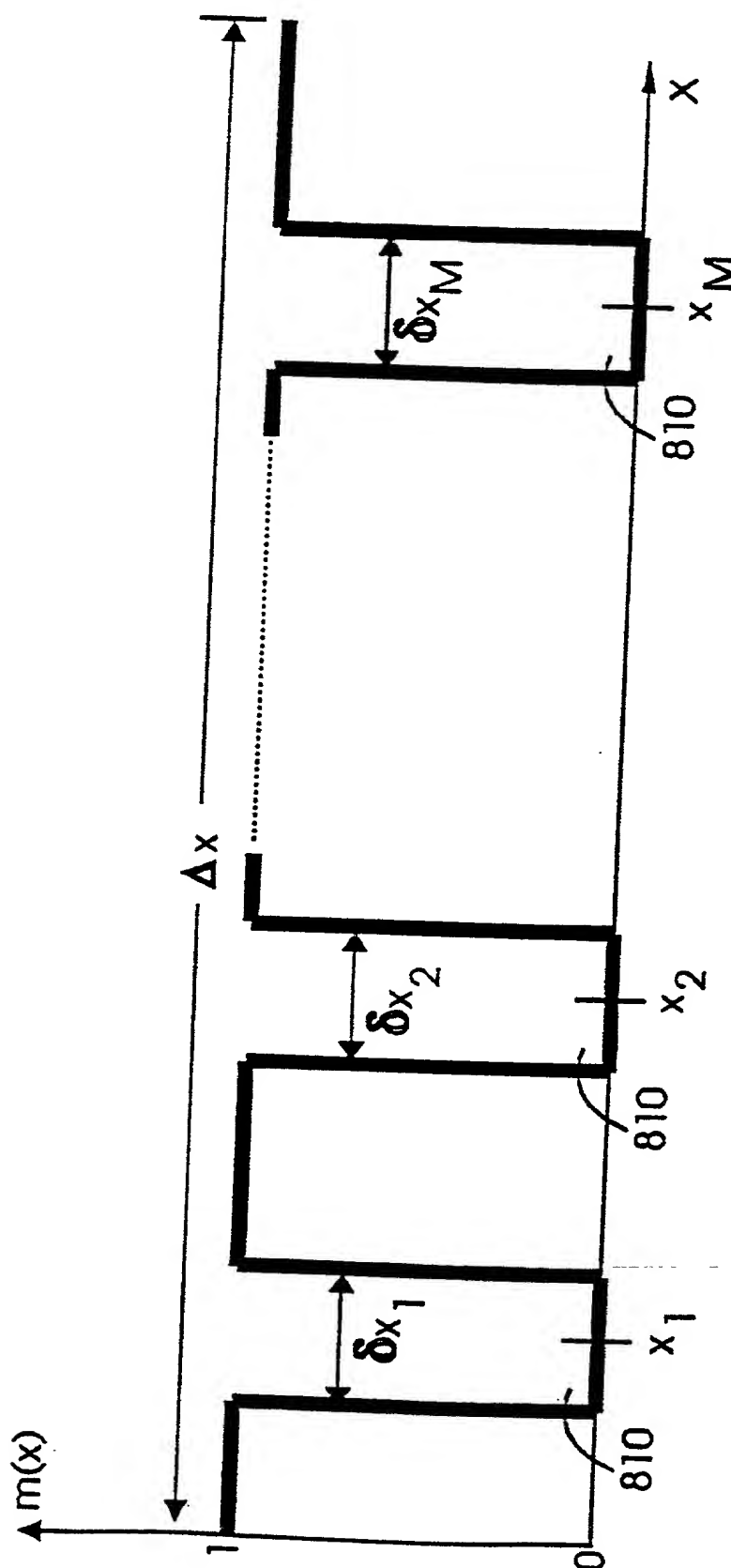


FIGURE 8

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FIG. 9A

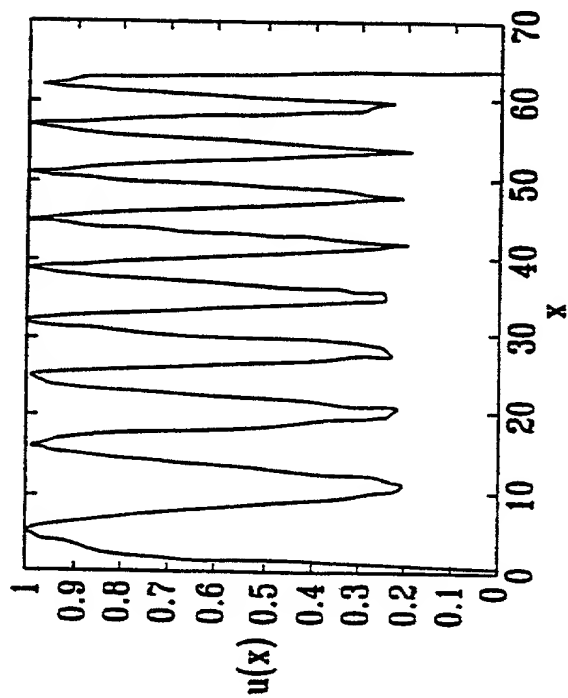


FIG. 9B

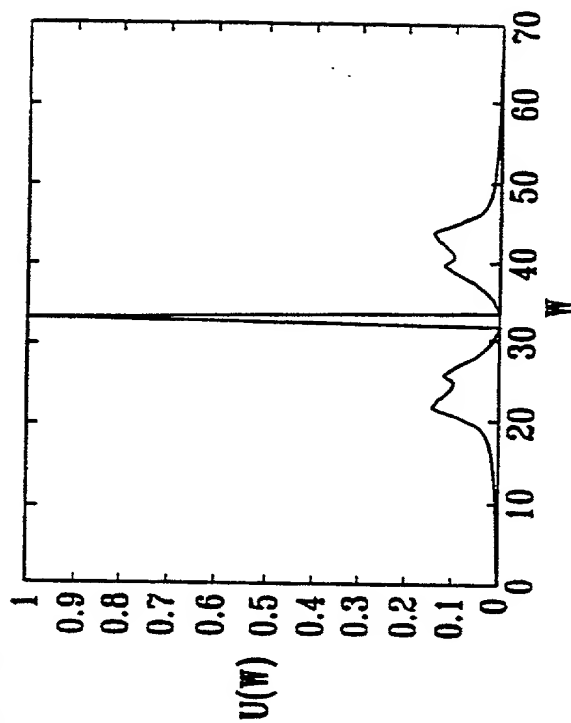


FIG. 9C

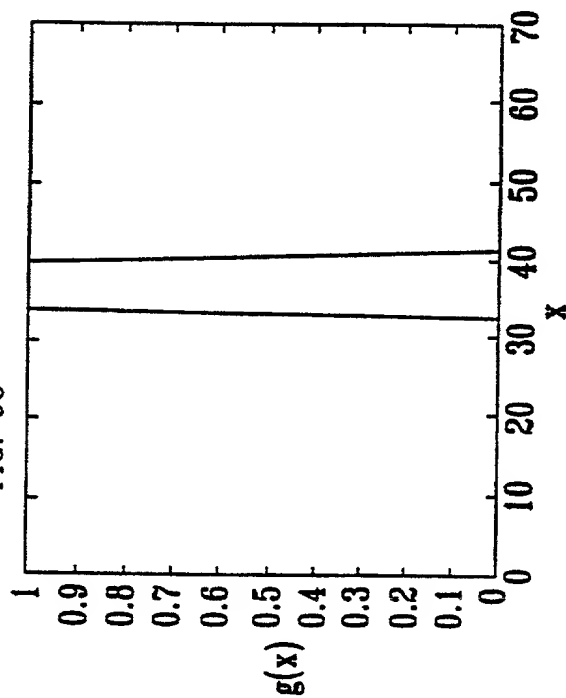
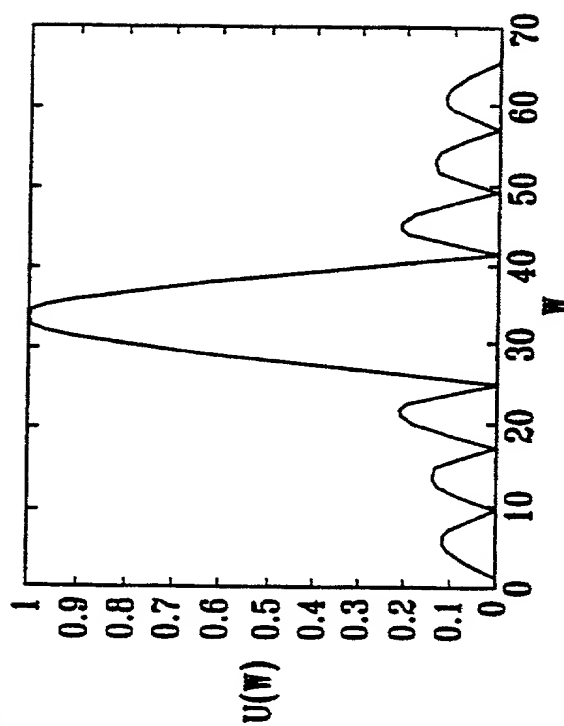


FIG. 9D



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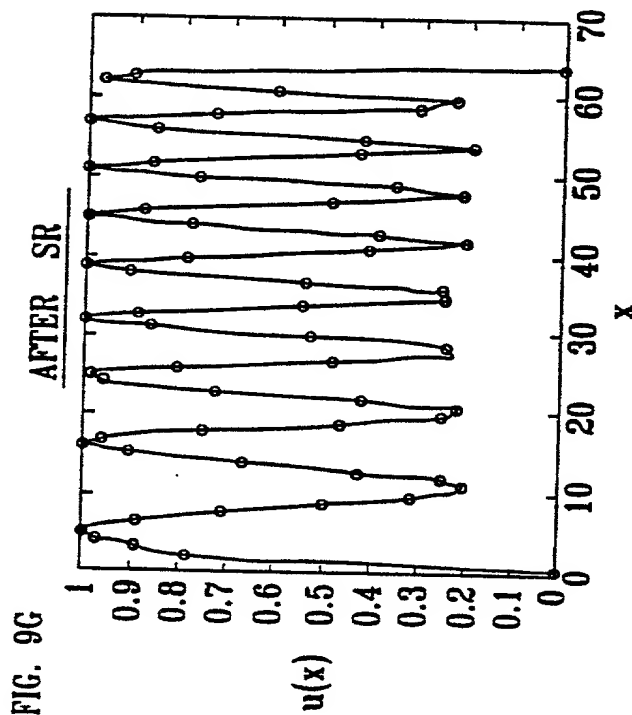
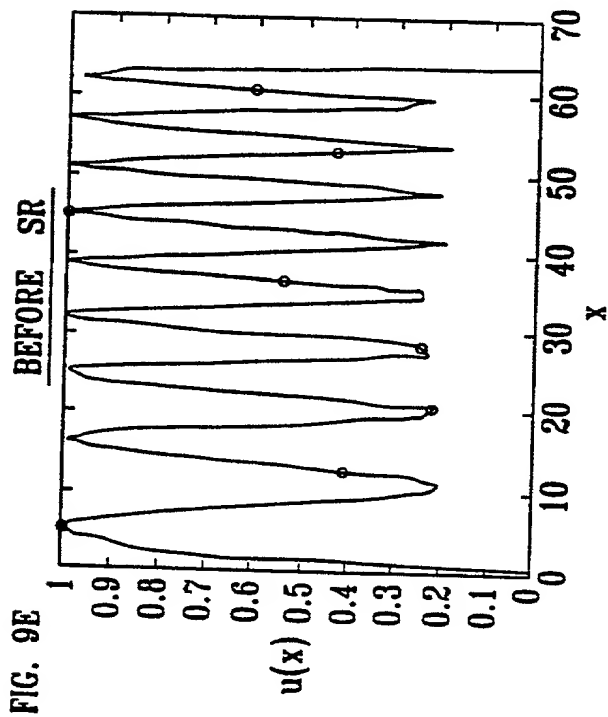
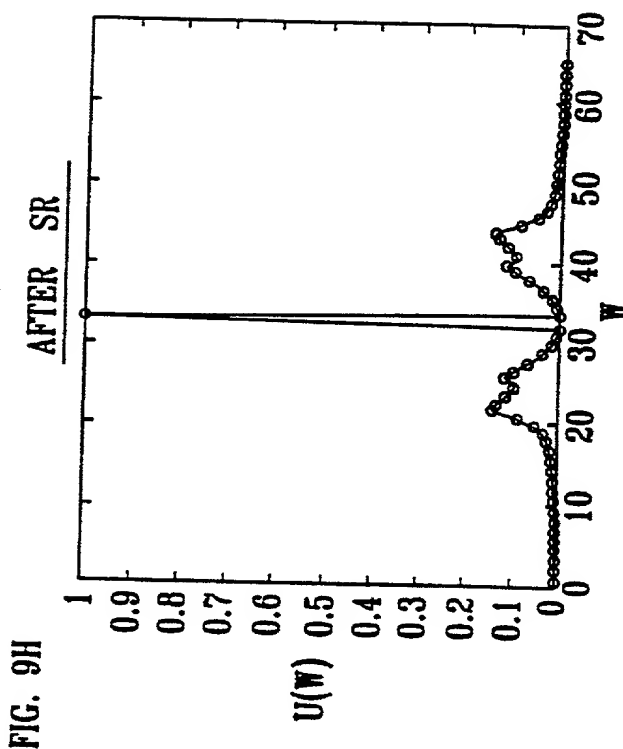
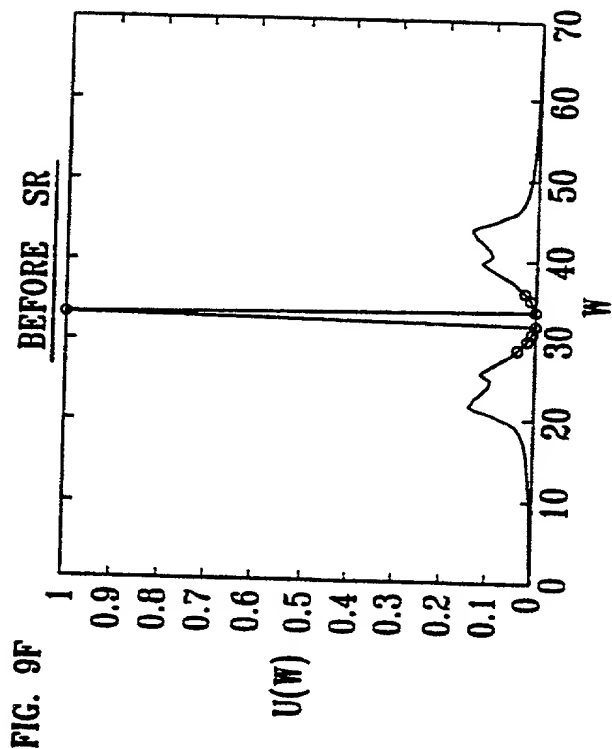


FIG. 9I

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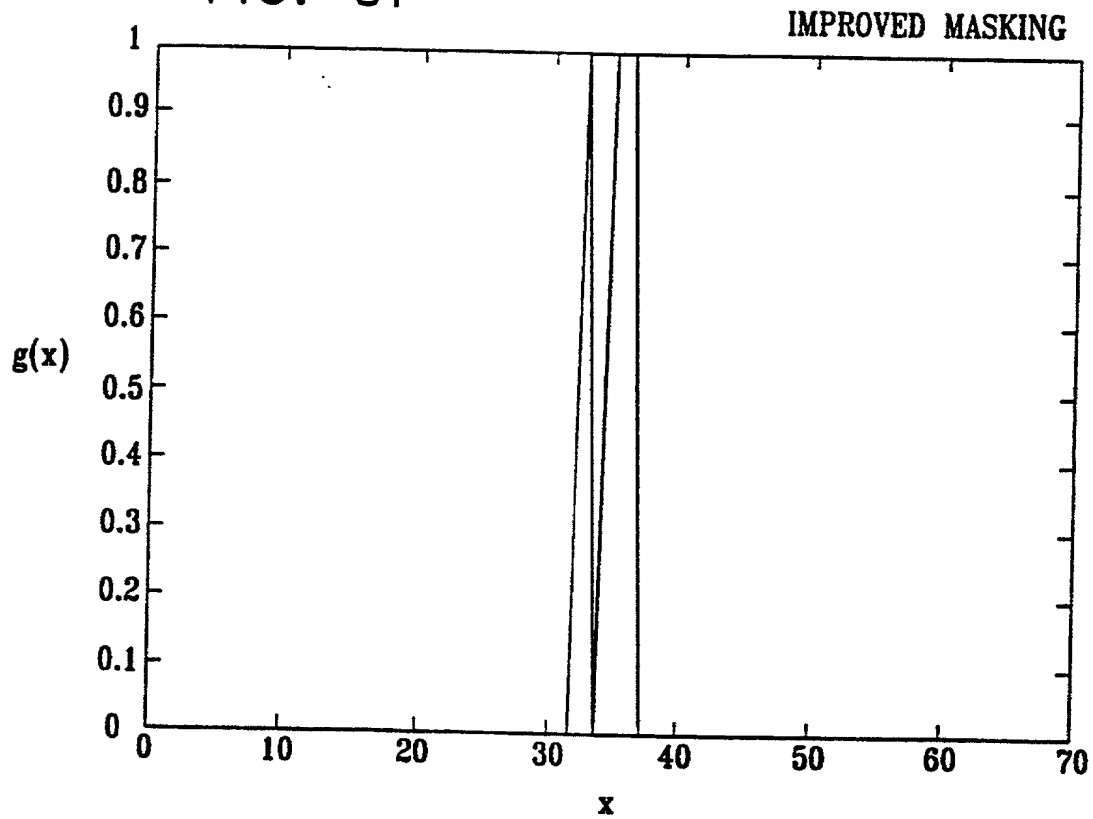
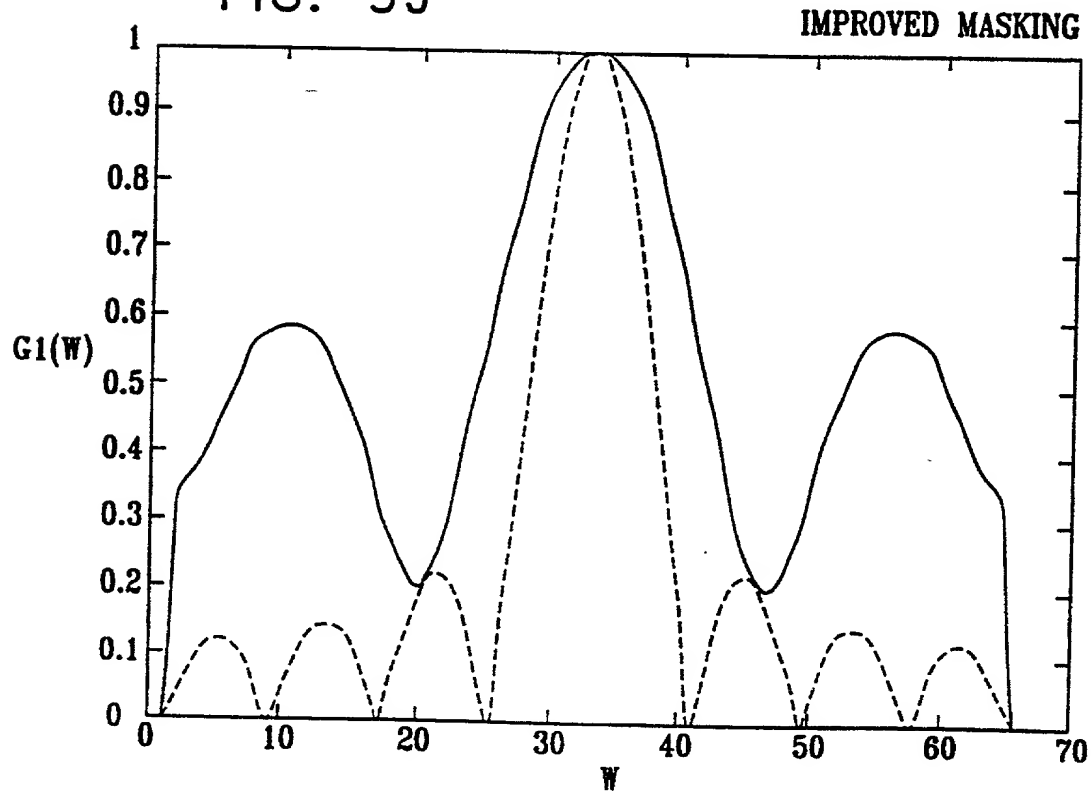


FIG. 9J



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FIG. 10



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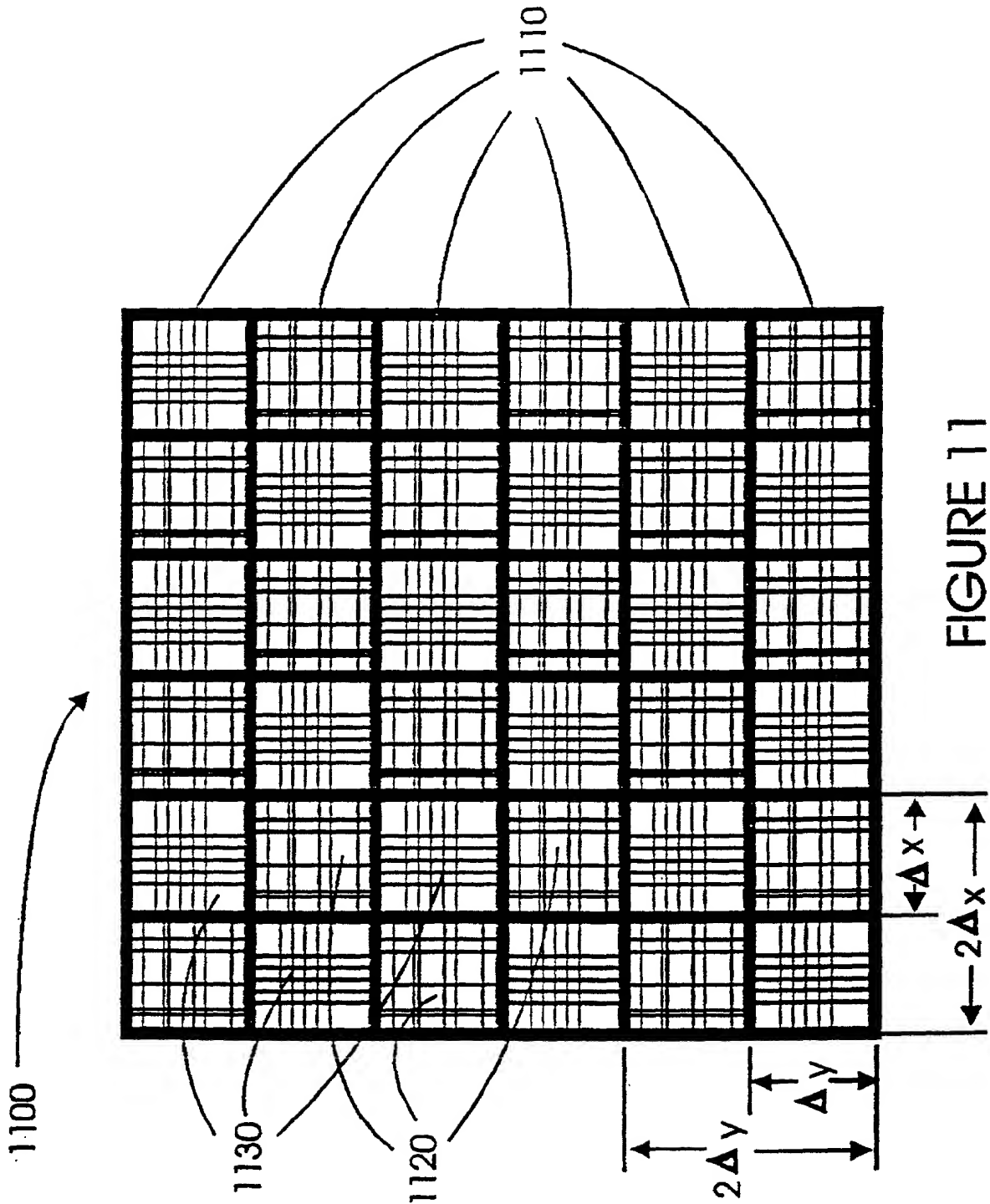


FIGURE 11

Practitioner's Docket No. _____

PATENT

Optional Customer No. Bar Code



00140

PATENT TRADEMARK OFFICE

COMBINED DECLARATION AND POWER OF ATTORNEY

(ORIGINAL, DESIGN, NATIONAL STAGE OF PCT, SUPPLEMENTAL, DIVISIONAL,
CONTINUATION, OR C-I-P)

As a below named inventor, I hereby declare that:

TYPE OF DECLARATION

This declaration is of the following type:

(check one applicable item below)

- ☐ original.
☐ design.

NOTE: With the exception of a supplemental oath or declaration submitted in a reissue, a supplemental oath or declaration is not treated as an amendment under 37 CFR 1.312 (Amendments after allowance). M.P.R.P. Section 714.16, 7th Ed.

- ☐ supplemental.

NOTE: If the declaration is for an International Application being filed as a divisional, continuation or continuation-in-part application, do not check next item; check appropriate one of last three items.

- ☒ national stage of PCT.

NOTE: If one of the following 3 items apply, then complete and also attach ADDED PAGES FOR DIVISIONAL, CONTINUATION OR C-I-P.

NOTE: See 37 C.F.R. Section 1.63(d) (continued prosecution application) for use of a prior nonprovisional application declaration in the continuation or divisional application being filed on behalf of the same or fewer of the inventors named in the prior application.

- ☐ divisional.
☐ continuation.

NOTE: Where an application discloses and claims subject matter not disclosed in the prior application, or a continuation or divisional application names an inventor not named in the prior application, a continuation-in-part application must be filed under 37 C.F.R. Section 1.53(b) (application filing requirements-nonprovisional application).

- ☐ continuation-in-part (C-I-P).

(Declaration and Power of Attorney--page 1 of 8) 1-1

INVENTORSHIP IDENTIFICATION

WARNING: *If the inventors are each not the inventors of all the claims, an explanation of the facts, including the ownership of all the claims at the time the last claimed invention was made, should be submitted.*

My residence, post office address and citizenship are as stated below, next to my name. I believe that I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter that is claimed, and for which a patent is sought on the invention entitled:

TITLE OF INVENTION

A METHOD AND SYSTEM FOR SUPER RESOLUTION

SPECIFICATION IDENTIFICATION

The specification of which:

(complete (a), (b), or (c))

(a) ☐ is attached hereto.

NOTE: *"The following combinations of information supplied in an oath or declaration filed on the application filing date with a specification are acceptable as minimums for identifying a specification and compliance with any one of the items below will be accepted as complying with the identification requirement of 37 C.F.R. Section 1.63:*

"(1) name of inventor(s), and reference to an attached specification which is both attached to the oath or declaration at the time of execution and submitted with the oath or declaration on filing;

"(2) name of inventor(s), and attorney docket number which was on the specification as filed; or

"(3) name of inventor(s), and title which was on the specification as filed."

Notice of July 13, 1995 (1177 O.G. 60).

(b) ☒ was filed on Sept. 27 2001, ☒ as Application No. 09/937,580
☐ and was amended on _____ (if applicable).

NOTE: *Amendments filed after the original papers are deposited with the PTO that contain new matter are not accorded a filing date by being referred to in the declaration. Accordingly, the amendments involved are those filed with the application papers or, in the case of a supplemental declaration, are those amendments claiming matter not encompassed in the original statement of invention or claims. See 37 C.F.R. Section 1.67.*

NOTE: *"The following combinations of information supplied in an oath or declaration filed after the filing date are acceptable as minimums for identifying a specification and compliance with any one of the items below will be accepted as complying with the identification requirement of 37 C.F.R. Section 1.63:*

(A) application number (consisting of the series code and the serial number, e.g., 08/123,456);

(B) serial number and filing date;

(C) attorney docket number which was on the specification as filed;

(D) title which was on the specification as filed and reference to an attached specification which is both attached to the oath or declaration at the time of execution and submitted with the oath or declaration; or

(E) title which was on the specification as filed and accompanied by a cover letter accurately identifying the application for which it was intended by either the application number (consisting of the series code and the serial number, e.g., 08/123,456), or serial number and filing date. Absent any statement(s) to the contrary, it will be presumed that the application filed in the PTO is the application which the inventor(s) executed by signing the oath or declaration.

M.P.E.P. Section 601.01(a), 7th ed.

- (c) ☐ was described and claimed in PCT International Application No. _____ filed on _____ and as amended under PCT Article 19 on _____ (if any).

SUPPLEMENTAL DECLARATION (37 C.F.R. Section 1.67(b))

(complete the following where a supplemental declaration is being submitted)

- ☐ I hereby declare that the subject matter of the

- ☐ attached amendment
☐ amendment filed on _____.

was part of my/our invention and was invented before the filing date of the original application, above identified, for such invention.

ACKNOWLEDGMENT OF REVIEW OF PAPERS AND DUTY OF CANDOR

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information, which is material to patentability as defined in 37, Code of Federal Regulations, Section 1.56,

(also check the following items, if desired)

- ☐ and which is material to the examination of this application, namely, information where there is a substantial likelihood that a reasonable Examiner would consider it important in deciding whether to allow the application to issue as a patent, and
- ☐ in compliance with this duty, there is attached an information disclosure statement, in accordance with 37 C.F.R. Section 1.98.

PRIORITY CLAIM (35 U.S.C. Section 119(a)-(d))

NOTE: "The claim to priority need be in no special form and may be made by the attorney or agent if the foreign application is referred to in the oath or declaration as required by Section 1.63. The claim for priority and the certified copy of the foreign application specified in 35 U.S.C. Section 119(b) must be filed in the case of an interference (Section 1.630), when necessary to overcome the date of a reference relied upon by the examiner, when specifically required by the examiner, and in all other situations, before the patent is granted. If the claim for priority or the certified copy of the foreign application is filed after the date the issue fee is paid, it must be accompanied by a petition requesting entry and by the fee set forth in Section 1.17(i). If the certified copy is not in the English language, a translation need not be filed except in the case of interference; or when necessary to overcome the date of a reference relied upon by the examiner; or when specifically required by the examiner, in which event an English language translation must be filed together with a statement that the translation of the certified copy is accurate." 37 C.F.R. Section 1.55(a).

I hereby claim foreign priority benefits under Title 35, United States Code, Section 119(a)-(d) of any foreign application(s) for patent or inventor's certificate or of any PCT international application(s) designating at least one country other than the United States of America listed below and have also identified below any foreign application(s) for patent or inventor's certificate or any PCT international application(s) designating at least one country other than the United States of America filed by me on the same subject matter having a filing date before that of the application(s) of which priority is claimed.

(complete (d) or (e))

(Declaration and Power of Attorney—page 3 of 8) 1-1

**ALL FOREIGN APPLICATION(S), IF ANY, FILED MORE THAN 12 MONTHS
(6 MONTHS FOR DESIGN) PRIOR TO THIS U.S. APPLICATION**

NOTE: *If the application filed more than 12 months from the filing date of this application is a PCT filing forming the basis for this application entering the United States as (1) the national stage, or (2) a continuation, divisional, or continuation-in-part, then also complete ADDED PAGES TO COMBINED DECLARATION AND POWER OF ATTORNEY FOR DIVISIONAL, CONTINUATION OR C-I-P APPLICATION for benefit of the prior U.S. or PCT application(s) under 35 U.S.C. Section 120.*

POWER OF ATTORNEY

I hereby appoint the following practitioner(s) to prosecute this application and transact all business in the Patent and Trademark Office connected therewith.

(list name and registration number)

JOSEPH H. HANDELMAN, 26179

JULIAN H. COHEN, 20302

JOHN RICHARDS, 31053

WILLIAM R. EVANS 25858

RICHARD J. STREIT, 25765

JANET I. CORD, 33778

PETER D. GALLOWAY, 27885

CLIFFORD J. MASS, 30086

IAIN C. BAILLIE, 24090

CYNTHIA R. MILLER, 34678

RICHARD P. BERG, 28145

(Check the following item, if applicable)

- ☐ I hereby appoint the practitioner(s) associated with the Customer Number provided below to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith.
- ☐ Attached, as part of this declaration and power of attorney, is the authorization of the above-named practitioner(s) to accept and follow instructions from my representative(s).

NOTE: *"Special care should be taken in continuation or divisional applications to ensure that any change of correspondence address in a prior application is reflected in the continuation or divisional application. For example, where a copy of the oath or declaration from the prior application is submitted for a continuation or divisional application filed under 37 CFR 1.53(b) and the copy of the oath or declaration from the prior application designates an old correspondence address, the Office may not recognize, in the continuation or divisional application, the change of correspondence address made during the prosecution of the prior application. Applicant is required to identify the change of correspondence address in the continuation or divisional application to ensure that communications from the Office are mailed to the current correspondence address. 37 CFR 1.63(d)(4)." Section 601.03, M.P.E.P., 7th Ed*

SEND CORRESPONDENCE TO

Ladas & Parry
26 West 61st Street
New York, N.Y. 10023

DIRECT TELEPHONE CALLS TO:

(Name and telephone number)

Julian H. Cohen
(212) 708-1887

(complete the following if applicable)

Since this filing is a [] continuation [] divisional there is attached hereto a Change of Correspondence Address so that there will be no question as to where the PTO should direct all correspondence.

DECLARATION

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

3.JAN.2002 16:03

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.on856

P.2

SIGNATURE(S)

NOTE: Carefully indicate the family (or last) name, as it should appear on the filing receipt and all other document.

NOTE: Each inventor must be identified by full name, including the family name, and at least one given name without abbreviation together with any other given name or initial, and by his/her residence, post office address and country of citizenship. 37 C.F.R. Section 1.63(a)(3).

NOTE: Inventors may execute separate declarations/oaths provided each declaration/oath sets forth all the inventors. Section 1.63(a)(3) requires that a declaration/oath, inter alia, identify each inventor and prohibits the execution of separate declarations/oaths which each sets forth only the name of the executing inventor. 62 Fed. Reg. 53,131, 53,142, October 10, 1997.

Full name of sole or first inventor

David (Given Name) MENDLOVIC (Family (Or Last Name))
Inventor's signature (x) [Signature]
Date (x) 17/12/01 Country of Citizenship Israel
Residence Petach Tikva (IL) TLX
Post Office Address IDELMAN ST. 9, 49550 Petach Tikva Israel

Full name of second joint inventor, if any

Zeev (Given Name) ZALEVSKY (Family (Or Last Name))
Inventor's signature (x) [Signature]
Date (x) 17/12/01 Country of Citizenship 1 Israel
Residence Rosh Haayin (IL) TLX
Post Office Address Hermon St. 1, 48560 Rosh Haayin Israel

Full name of third joint inventor, if any

(Given Name) (Middle Initial or Name) Family (Or Last Name)
Inventor's signature (x)
Date (x) Country of Citizenship ISRAEL
Residence
Post Office Address

*(check proper box(es) for any of the following added page(s)
that form a part of this declaration)*

- ☐ Signature for fourth and subsequent joint inventors. *Number of pages added* _____
* * *
- ☐ Signature by administrator(trix), executor(trix) or legal representative for deceased or incapacitated inventor. *Number of pages added* _____
* * *
- ☐ Signature for inventor who refuses to sign or cannot be reached by person authorized under 37 C.F.R. Section 1.47. *Number of pages added* _____
* * *
- ☐ Added page for signature by one joint inventor on behalf of deceased inventor(s) where legal representative cannot be appointed in time. (37 C.F.R. Section 1.47)
* * *
- ☐ Added pages to combined declaration and power of attorney for divisional, continuation, or continuation-in-part (C-I-P) application.
☐ Number of pages added _____
* * *
- ☐ Authorization of practitioner(s) to accept and follow instructions from representative.

*(If no further pages form a part of this Declaration,
then end this Declaration with this page and check the following item)*

☒ This declaration ends with this page.